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A NOVEL FM/AM
TELEMETRY TRANSMITTER

BY

ROBERT L. LOUNSBERY

A thesis submitted
in partial fulfillment of the requirements for the
degree Master of Science, Department of
Electrical Engineering, South Dakota
State University

1970

A NOVEL FM/AM

TELEMETRY TRANSMITTER

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Advisor

Date

Head, Electrical Engineering
Department

Date

2661-11

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R.L.L.

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CHAPTER I

INTRODUCTION

The transmission of information is in many cases vital to modern research. An example is the transmission of information which concerns the physiological phenomena taking place inside the body of an unrestrained animal. The transmission of the information has to be accomplished with a minimum amount of discomfort to the animal. A physical connection to the sensor would cause much discomfort to the animal and would not indicate a normal situation. Therefore, in recent years the information gained from a sensor (inside of an animal's body) has been used as the intelligence to modulate a small telemetry unit. This information is transmitted to a receiving station outside of the animal. The mode of transmission and the type of sensor have varied.

The type of sensor to be used will vary with the body function that is to be observed and the type of transmitter to be used. Two important body functions are temperature and pressure. Most of the temperature sensors used in the past have been thermistors⁸. They have been used to frequency modulate different types of oscillators or change the pulse duration time in a pulse code modulation system, such as the one developed at NASA Ames Research Center¹⁴.

A pressure sensitive coil was one of the first pressure transducers^{10,11}. A metal slug that moves as a result of a pressure change was placed inside of a coil. Thus, a change in pressure changed the

inductance of the coil. If the coil was in the tank circuit of an oscillator, the frequency of oscillation would vary with pressure. However, the inductor was very bulky and therefore not conducive to miniaturization. With this in mind, the remaining component of a tank circuit was investigated. Although this paper was not primarily directed toward sensors, the variable capacitor was investigated. It was found that the foremost disadvantage of the variable capacitor in the past was its small change in capacitance with temperature or pressure. However, this becomes an advantage in the system that is developed in Chapter II.

It is important to note that the sensor and transmitter must be compatible. R. S. MacKay developed a versatile transmitting unit¹⁴. It is a single stage frequency modulated oscillator. The modulation can be obtained from three different types of sensors; a variable resistance for temperature measurements, a variable inductance for pressure measurements or a variable resistance between two electrodes for pH measurements. In many measurement applications, a single stage, frequency modulated transmitter has been used^{4,5} with emphasis placed on small size and long battery life. However, the gathering of data is rather laborious and quite sophisticated equipment is required to receive and demodulate the data. In obtaining the data, one first zero beats the receiver using the beat frequency oscillator. Secondly, without further receiver adjustment, a signal generator is tuned until the receiver is again at zero beat. Then, this frequency is

measured. This method is very time-consuming and renders continuous recording nearly impossible because of the instability of the radio frequency and the beat frequency oscillators.

The above method has been used^{2,3} where readings were taken every half hour which means that a minima or maxima in the intelligence signal could have been missed. Therefore, a more sophisticated transmitter is required so that a continuous record can be made with available equipment. For example, a frequency modulated subcarrier/ amplitude modulated carrier system (FM/AM) constitutes a more complicated transmitter. It requires more operating current but requires less complicated receiving equipment.

The FM/AM transmitter has been used as a temperature and a pressure sensing telemetry system^{8,9}. This system is composed of two oscillators: a sensing and a transmitting oscillator. A phase shift oscillator with a variable resistance as the sensor is used as the sensing oscillator. The frequency of the oscillator has to be in the audio range to utilize available receivers and easily implement the recording of the information. The output of the sensing oscillator is used to amplitude modulate the transmitting oscillator. Overall operation is much better than the single staged frequency modulated transmitter.

The FM/AM transmitter has its disadvantages. The main one is that the first stage (the phase shift oscillator) requires five times the current of the transmitting oscillator for operation. The total current required by both oscillators is excessive. Also, to use the

transmitter as a pressure sensing device is very difficult and expensive. A pressure sensitive capacitor cannot be used because of its small change in capacitance. Pressure sensitive potentiometers are available on the commercial market and have been used with satisfactory results. However, they are quite expensive.

The FM/AM telemetry transmitter has proven to be a very satisfactory temperature sensitive telemetry system, barring the larger current and larger size. It would be advantageous to have a smaller more efficient FM/AM system while retaining its advantage of ease of recording data.

The purpose of this thesis will be to develop a low current FM/AM system to be used as an implanted biotelemetry unit. The circuit will be designed in Chapter II and then an equivalent model will be developed in Chapter III. Chapter IV will be devoted to experimental work and discussion of the results.

CHAPTER II

DESIGN

A. Design Criteria

Before the design of an implanted biotelemetry unit is considered, it is essential to establish some fundamental design criteria or considerations. Most of these criteria are found from a literature review of the subject. The four most important criteria are size, output signal, power requirement and versatility.

1. Size

Knowledge of the temperature and pressure variations in and on various organs of the animal body is important in the study of animal science. In past years studies have been made on the larger organs of animals (for example, the rumen of a cow). However, it is (and has been) desirable to do similar studies on smaller organs of animals. To make this possible, a small transmitter and a small sensor is needed. The size of present transmitters is in the order of 10 cm long and 2.5 cm in diameter⁹ for the studies conducted on cows. For the study of smaller animals, this would have to be reduced by one half or more.

2. Signal Output

Although the size of the transmitter is an important consideration, there are other considerations that have to be made. One is the type of output signal. As already discussed, the transmitter

could be made very small and still not be acceptable because of the difficulties in acquiring data. Amplitude modulation receivers are readily available on the market. Therefore, an output, amplitude modulated at an audible rate compatible with the frequency response of available receivers, is desirable.

3. Power Requirement

In the development of the amplitude modulated signal, it is also desirable to keep the current at a minimum to insure long battery life. If the transmitter is made small enough it can be implanted in various parts of the body and if the current drain is low enough it will remain operational for a long period of time.

4. Versatility

Another attribute that is desired in a telemetry unit of this type is versatility. With the two main physiological phenomena, pressure and temperature, it would be ideal if the transmitter could be used for both, with a minimum of component change. Temperature sensitive, variable capacitors are available and preliminary investigations indicated that a pressure sensitive capacitor can be built. Therefore, the preliminary design incorporated a variable capacitor.

B. Initial Design

The initial design is as shown in Fig. 2-1. The sensing oscillator signal is mixed with a crystal controlled oscillator signal. The sensing oscillator varies from one to ten KHz above the crystal

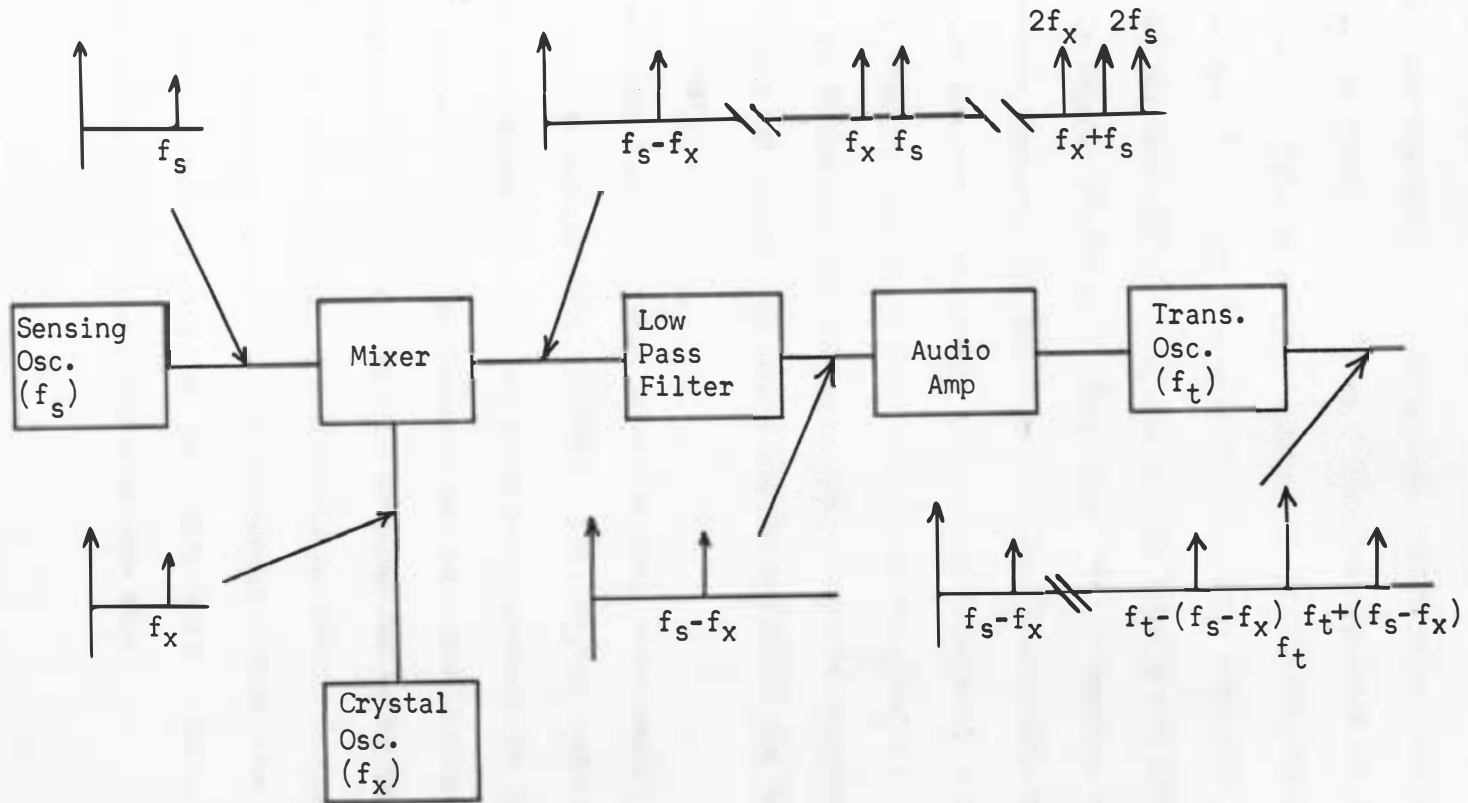


Fig. 2-1 Initial FM/AM Design.

oscillator frequency. The reason for using this frequency range is to stay within the bandpass of commercially available receivers.

Following the mixer, a low pass filter is required to insure that only the audio frequency is passed on to the audio amplifier. It is a well-known fact that the output of a mixer consists of the frequencies of the two inputs, the sum of the inputs and the difference of the inputs as shown in Fig. 2-1. The frequency of concern is the difference between the two inputs which is an audio frequency between one and ten KHz. The audio difference frequency signal could then be used to amplitude modulate an RF oscillator. An audio amplifier following the low pass filter may be required if the output is not of sufficient amplitude to modulate the transmitting oscillator.

The resulting carrier signal would be amplitude modulated by a frequency modulated subcarrier, (FM/AM). This method and design as shown in Fig. 2-1 appeared to be an excellent approach to FM/AM modulation. However, after development of the circuit began, it became apparent that the battery current consumption would be rather high and the size of the total system would be fairly large. For this system to obtain a lower current consumption than the phase shift oscillator technique would be very difficult. Also, the oscillators and audio filter would increase the size.

C. Final Design

1. Sensing Oscillator

The first stage was chosen to be a colpitts type oscillator because of its relative circuit simplicity as shown in Fig. 2-2a. The equivalent circuit of the oscillator is shown in Fig. 2-2b and its resonant frequency and starting condition are⁶

$$f_0 \doteq \frac{1}{2\pi} \sqrt{\frac{C + C_5}{LC C_5}} \quad (2-1)$$

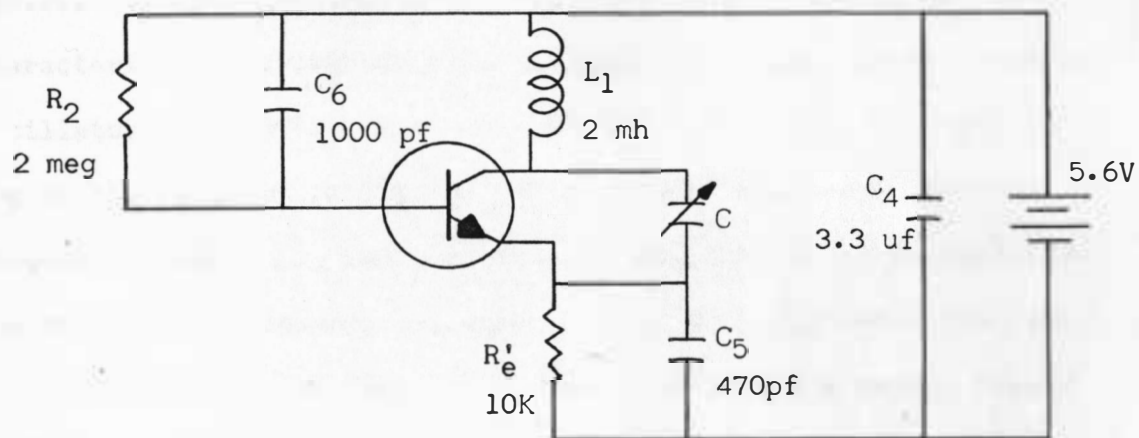
$$\beta < \frac{C_5}{C} \quad (2-2)$$

The tank capacitor (C) in Fig. 2-2a was chosen as the sensing capacitor. The oscillator circuit was designed to keep C as small as possible. The output of the sensing oscillator is frequency modulated and with the capacitor C very small, the current is low⁹ (15 micro amperes).

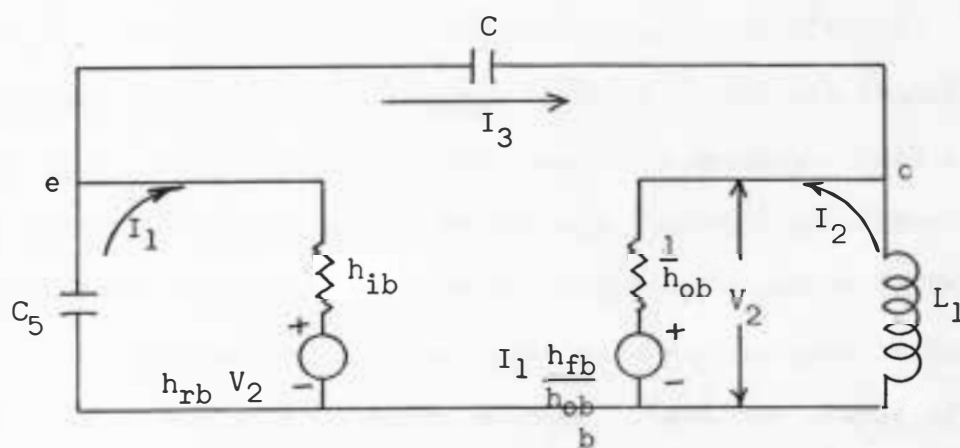
With the first stage decided upon, the problem of how to use this frequency modulated signal to amplitude modulate an output signal remained.

2. Mixer and Modulator

With the consideration of low current consumption and small size, an attempt to combine or eliminate some of the stages of the initial design seemed necessary. Initially, the mixer and local oscillator were combined into one circuit.



(a)



(b)

Fig. 2-2 (a.) Sensing Oscillator
 (b.) Low Frequency Equivalent Circuit

A crystal controlled, colpitts type oscillator was designed to minimize current consumption and to insure that a nonlinear input characteristic was available for mixing. The output of the sensing oscillator was fed into the base circuit of the crystal controlled oscillator as shown in Fig. 2-3 at a voltage level such that the frequencies would mix and a difference frequency would be realized. The difference frequency was again restricted to an audio frequency.

In analyzing the circuit, it was noted that the energy stored in the near field of the coil (L_2) was the desired output signal as shown in the second trace of Fig. 2-4. This signal was observed by placing a search coil near the coil (L_2) of the crystal oscillator. The carrier frequency was the same as the crystal frequency and the modulation frequency was the difference between the sensing oscillator frequency and the crystal frequency. If the sensing oscillator is designed to not vary more than ten KHz above the crystal oscillator, this output signal satisfies the original design requirements.

Fig. 2-4 shows four oscilloscope displays of signals associated with the FM/AM system Fig. 2-3. The circuit is operating with a sensing oscillator frequency of 385 KHz and a crystal oscillator frequency of 380 KHz. The top display is the audio output (5 KHz) of a Hallicrafters WR3000 receiver. The receiver is tuned to the carrier (380 KHz) of the FM/AM transmitter. Thus, the output of the receiver is a signal at the difference frequency of the sensing oscillator and the crystal oscillator (5 KHz). The second display is of the near field of coil (L_2). This is obtained by

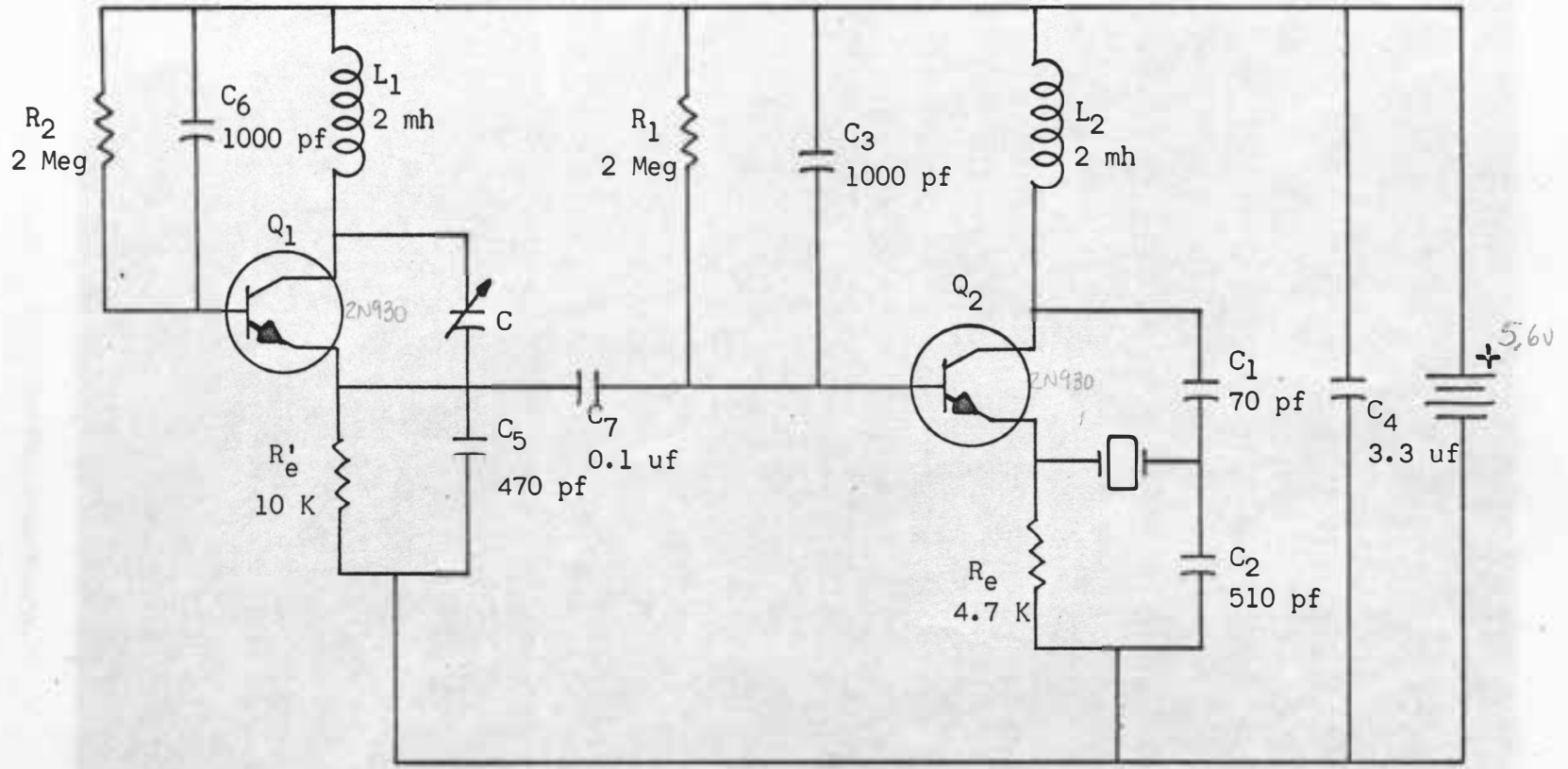


Fig. 2-3. Final Design of FM/AM System.

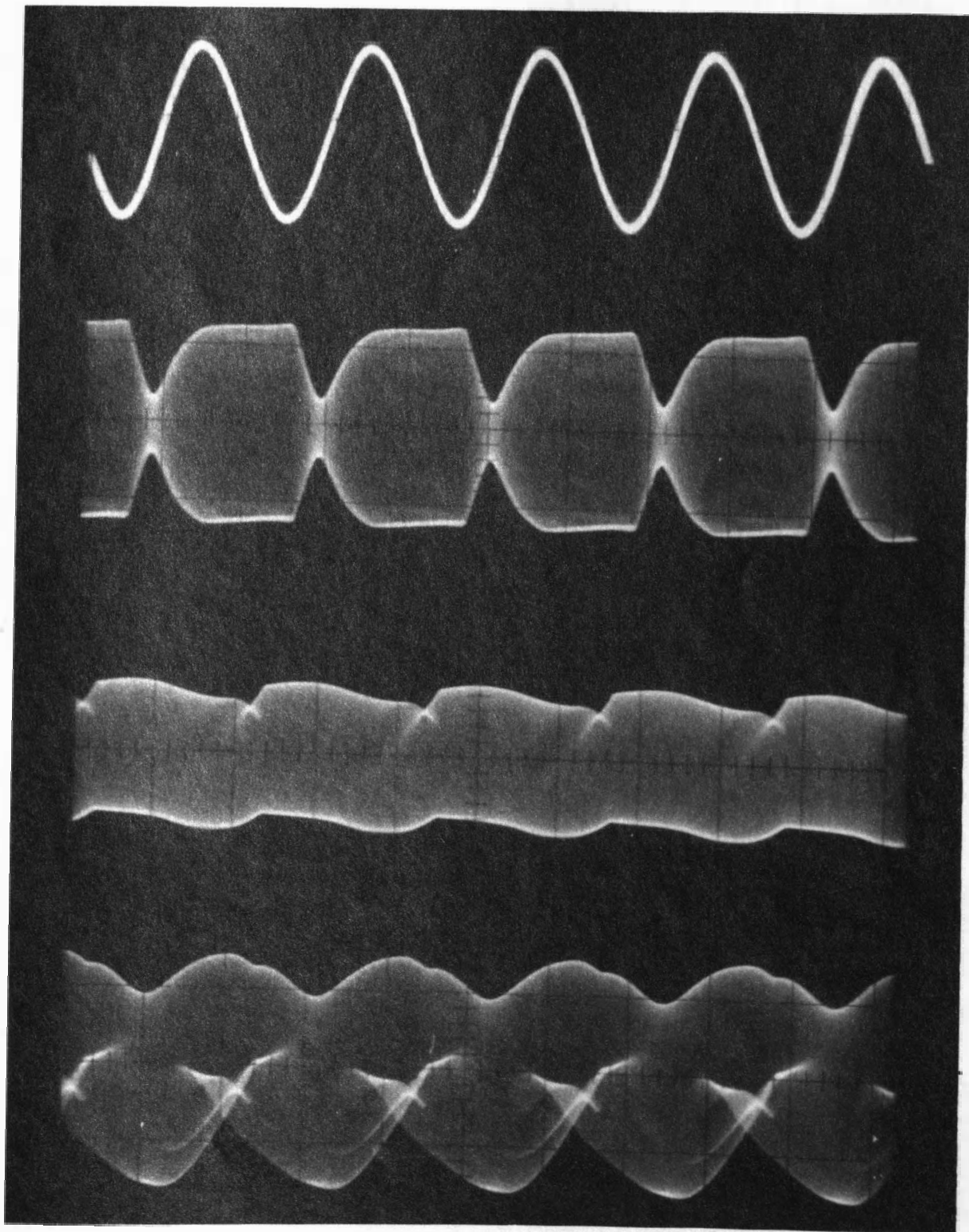


Fig. 2-4. FM/AM System Waveforms.

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placing a search coil close to the coil (L_2). The third display is the base to ground voltage. The fourth display is the voltage across the emitter resistor R_e in Fig. 2-3.

With the type of output signal desired available, the remaining design restrictions were size, low current consumption, and versatility in the type of phenomena that can be observed.

The battery current drain is very low. With a supply voltage of 5.6 volts D.C., the total current consumed is 30 microamperes. If the voltage is reduced to 1.4 volts, the current drain decreases to 10 microamperes. The unit must be built for a given voltage. If the voltage is changed after construction, the sensing oscillator will change frequencies. However, the capability of proper operation at a lower voltage is in itself an advantage over previous methods⁹.

If a high frequency is used, all circuit components are small with the crystal being the largest. Also, if the low voltage (1.4 volts D.C.) is used, the battery is one fourth the size of the 5.6 volts D.C. battery. Hence a small telemetry transmitter can be built.

With temperature and pressure sensitive capacitors available, the transmitters can be changed from a temperature sensing to a pressure sensing unit with a minimum of component changes. Thus, using the capacitor as the sensing element provides a versatile unit. A versatile system with a low current consumption that can be readily adapted to continuous data recording has been obtained.

Although the mixer is a frequently used device, the theory and design are not well documented. In the telemetry circuit developed in this chapter, first mixing occurs and then modulation, these processes are discussed in Chapter III.

CHAPTER III

EQUIVALENT MODEL

The conventional mixer in receivers is used to translate the incoming signal frequency spectra into an intermediate band of frequencies. Although the system that has been developed in Chapter II is not a conventional mixer, mixing does take place. Therefore, this chapter will first cover the conventional mixer theory. Secondly, it will relate the system to the conventional mixer; and, finally, amplitude modulation of the crystal controlled oscillator will be discussed.

A. The Conventional Mixer

In the available literature on mixers, most authors discuss the conventional mixer and/or the frequency converter. Mixing is defined as a process that transforms a band of frequencies centering about one frequency f_1 to another related band of frequencies centering about some other frequency f_2 . In most practical applications of the mixer, this does occur. The difference frequency is the frequency of interest and all other frequencies are filtered out. However, other possible applications do exist for the mixer circuit as will be shown.

The conventional mixer circuit can be used with a variety of input configurations: (a) one signal fed into the emitter and a second into the base, (b) both signals fed into the base circuit, (c) one signal fed into the collector circuit and a second into the base

circuit, etc. If capacitor coupling is employed, the first configuration is usually used, as shown in Fig. 3-1a. This configuration is used to obtain better isolation between the two sources. The circuit shown is similar to the conventional mixer used in the front end of a communications receiver.

To illustrate the operation of this configuration two signal generators can be used as the input signals. By Kirchoff's voltage law it can be seen that $V_b = V_s + V_o$, where V_b , V_s and V_o are defined in Fig. 3-1b.

The transistor Q_2 must be biased with proper values of R_1 and R_e such that a nonlinear base to emitter characteristic is available. Since a linear device never generates new frequencies, nonlinear properties are essential to the process of mixing. In some cases, the nonlinearity can be adequately approximated with the first and second order terms of a power series expansion.

$$i_c(t) = K_1 V_b(t) + K_2 V_b^2(t) \quad (3-1)$$

With $V_b(t) = V_s(t) + V_o(t)$ and $V_s(t) = V_{sm} \cos \omega_s t$, $V_o(t) = V_{om} \cos \omega_o t$ (the subscript m denotes maximum), we have

$$i_c(t) = K_1 (V_{sm} \cos \omega_s t + V_{om} \cos \omega_o t) + K_2 (V_{sm} \cos \omega_s t + V_{om} \cos \omega_o t)^2 \quad (3-2)$$

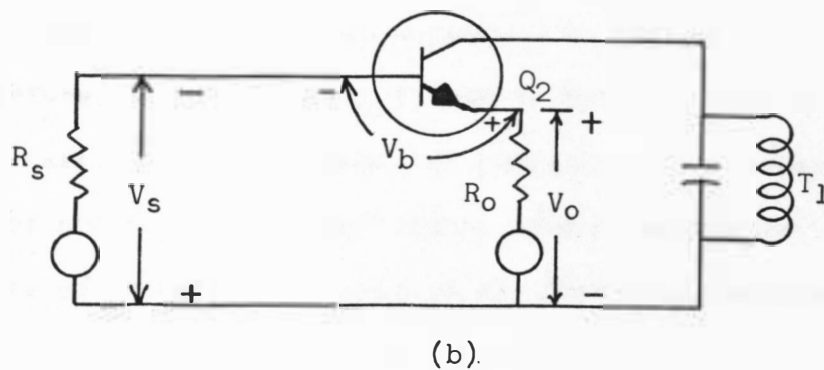
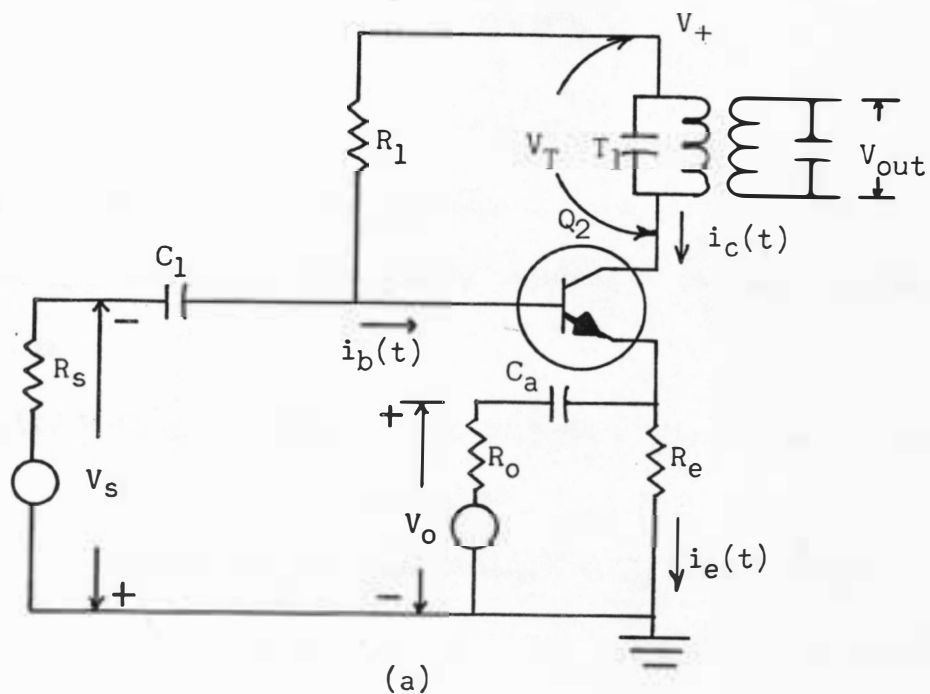


Fig. 3-1. (a) Conventional Mixer
(b) Mixer Equivalent

$$\begin{aligned}
 i_c(t) &= K_1 V_{sm} \cos \omega_s t + K_1 V_{om} \cos \omega_o t \\
 &+ K_2 V_{sm}^2 \cos^2 \omega_s t + K_2 V_{om}^2 \cos^2 \omega_o t \\
 &+ 2K_2 V_{sm} V_{om} \cos \omega_s t \cos \omega_o t
 \end{aligned}$$

Substitution of the trigonometric relations

$$\cos^2 \omega_s t = \frac{1}{2}(1 + \cos 2\omega_s t) \text{ and}$$

$$\cos \omega_s t \cos \omega_o t = \frac{1}{2} \cos(\omega_s + \omega_o)t + \cos(\omega_s - \omega_o)t$$

results in

$$\begin{aligned}
 i_c(t) &= K_1 V_{sm} \cos \omega_s t + K_1 V_{om} \cos \omega_o t + \frac{1}{2} K_2 V_{sm}^2 (1 + \cos 2\omega_s t) \\
 &+ \frac{1}{2} K_2 V_{om}^2 (1 + \cos 2\omega_o t) \\
 &+ K_2 V_{sm} V_{om} \cos(\omega_s + \omega_o)t + \cos(\omega_s - \omega_o)t \quad (3-3)
 \end{aligned}$$

It is apparent from equation 3-3 that new frequencies are produced.

The resultant frequencies are the two originals, their 2nd harmonics, a D.C. component, and the sum and the difference of the two original frequencies.

The difference frequency $(\omega_s - \omega_o)$ is denoted as ω_D . For conventional use, the tank circuit (T_1) is tuned to resonate at ω_D and thus, the tank circuit has a negligible impedance at other frequencies. Therefore, the voltage ($V_T(t)$) across the tank circuit exists only within a narrow band of frequencies centered at the frequency (ω_D) . The difference frequency (ω_D) signal will be amplified. The other signals generated in the mixing process are attenuated because of the output

impedance at these frequencies. The gain that is achieved is called conversion gain and is defined as the ratio:¹

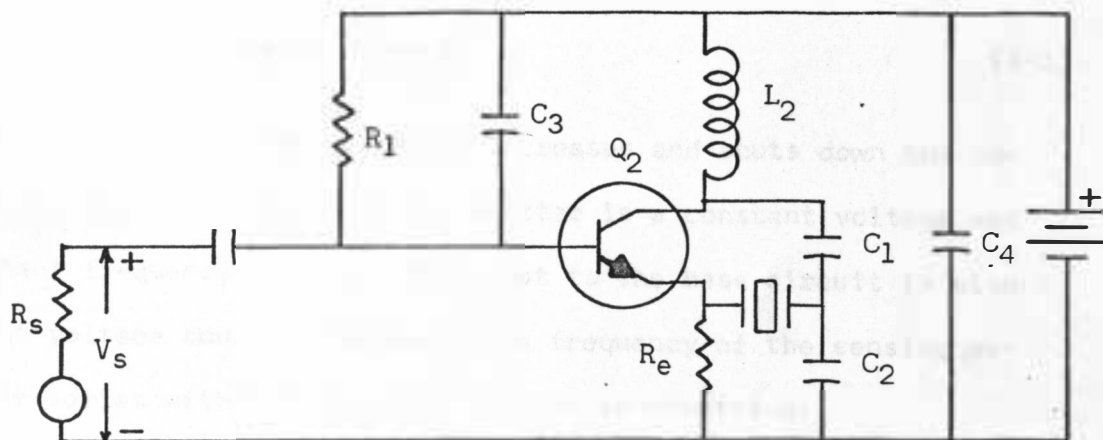
$$\text{Conversion gain} = \frac{\text{available power difference frequency from mixer(3-4)}}{\text{available power from signal source}}$$

The conventional mixer, when used in the front end of the super-heterodyne receiver has a modulated carrier (ω_s), as one of its inputs. The modulated carrier signal is combined with a locally generated signal (ω_o) to produce a new signal. The frequency of this signal is called the intermediate frequency (IF) and is always lower than the carrier frequency but has the same modulation. The IF signal is demodulated and an audio output is obtained.

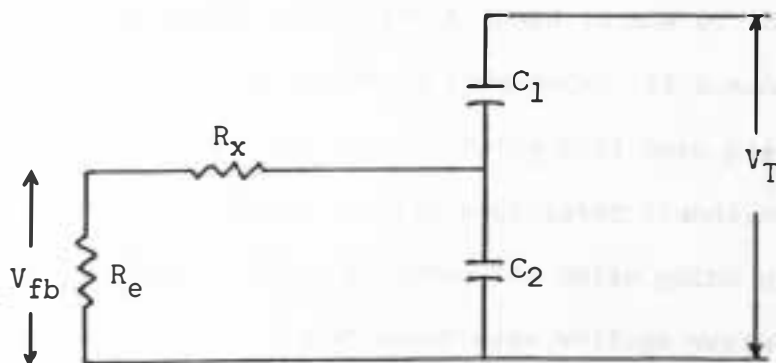
B. Conventional Mixer Versus Transmitter System

In the transmitter developed in Chapter II, mixing is the first operation that takes place. The mixing occurs in the transistor of the transmitting oscillator.

The transmitting oscillator can be represented by an amplifier with equivalent inputs and outputs. The emitter signal is an input from the feedback circuit of the crystal controlled oscillator. The base signal is an input from the feedback circuit of the sensing oscillator. Thus, the base input can be represented by an equivalent source as shown in Fig. 3-2a. Although the crystal controlled oscillator is a common base oscillator circuit, the base to ground impedance is approximately 400 ohms at the crystal and sensing oscillator frequencies. The input impedance to the base circuit is approximated by its smallest component, C_3 , in Fig. 3-2a.



(a)



(b)

Fig. 3-2. (a) Equivalent Base Input
 (b) Equivalent Emitter Input

The emitter input can also be represented by an equivalent source. A voltage (V_{fb}) is picked off the voltage divider C_1 and C_2 as shown in Fig. 3-2b. In the feedback circuit the crystal is shown as a small impedance (R_x) which is true at the crystal frequency⁷. For the case where $R_x = 0$

$$V_{fb} = \frac{C_1}{C_1 + C_2} V \quad (3-5)$$

At other frequencies the impedance increases and shuts down the oscillator. Thus, the input to the emitter is a constant voltage and a constant frequency source. The input to the base circuit is also a constant voltage source. However, the frequency of the sensing oscillator varies with the function that it is observing.

The collector output circuit is the tuned tank circuit of the oscillator. Therefore, it can be considered as a tank circuit tuned to the crystal frequency as shown in Fig. 3-3. Since the emitter input is at the crystal frequency, the tank circuit is tuned to the emitter input frequency. The circuit in Fig. 3-3 is the same as the conventional mixer with the tank circuit tuned to one of the original frequencies rather than the difference frequency. If a nonlinear base to emitter junction is available, mixing will take place.

The D.C. bias point of the crystal oscillator transistor (Q_2) is 0.4 volts and 2 microamps. This is below the cutin point of the silicon transistors used. Thus, a nonlinear base voltage versus base current is available as shown in Fig. 3-4. With the proper input voltage, mixing will occur.

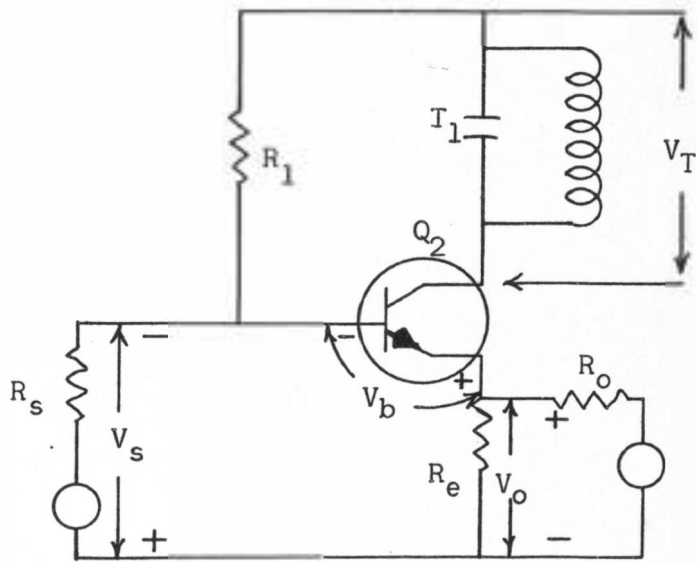


Fig. 3-3. Equivalent Inputs and Outputs of Q_2 .

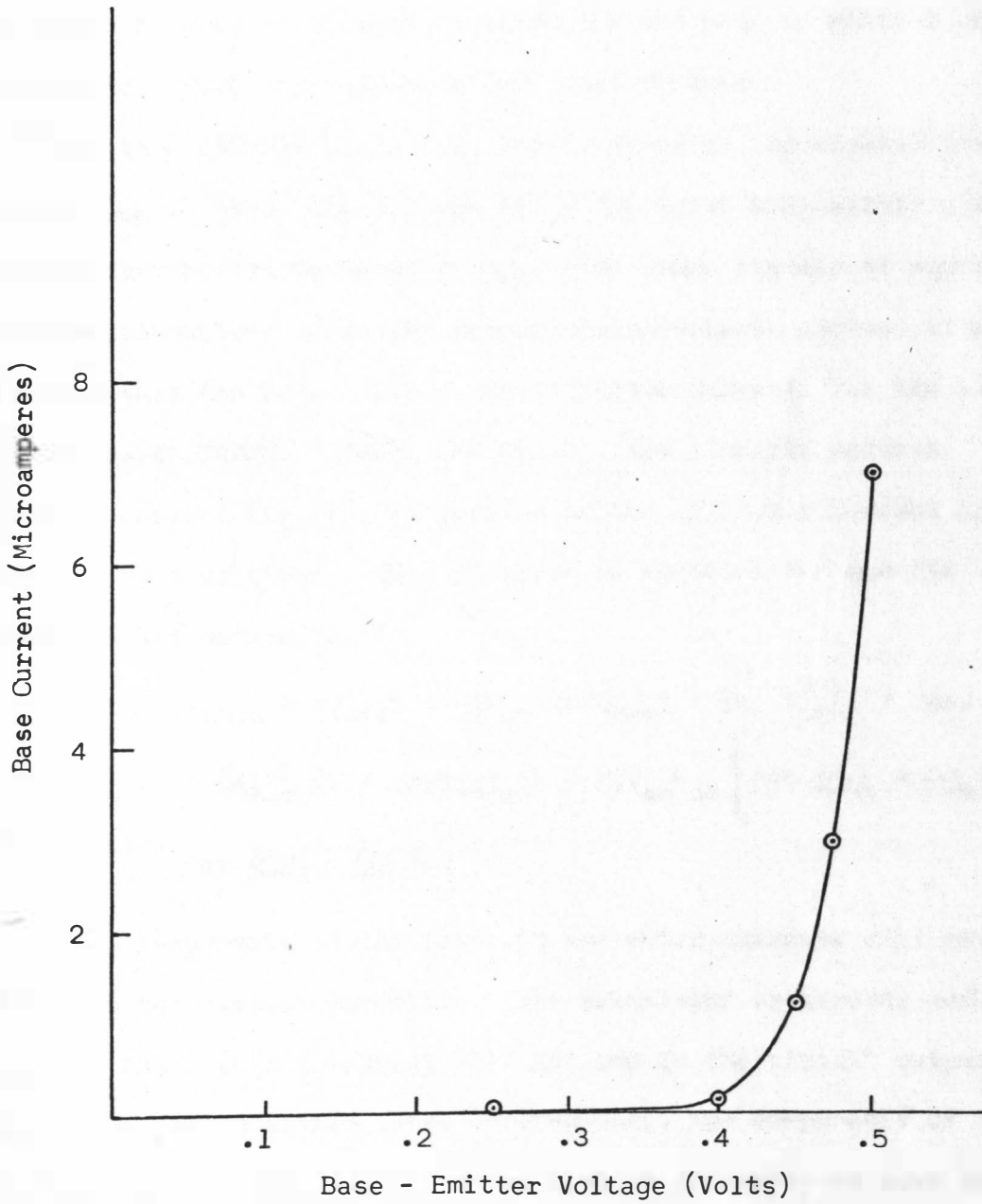


Fig. 3-4. Base - Emitter Characteristic of the 2n930 Transistor.

C. The Equivalent Mixer

The circuit in Fig. 3-3 will be used to explain the mixing operation. With a nonlinear characteristic available, equation 3-1 can again be used as an approximation for the base to emitter characteristic. From this equation 3-3 again follows.

The tank circuit T_1 in Fig. 3-3 is tuned to the crystal frequency (ω_0). Thus, the voltage $V_T(t)$ can exist only within a narrow band of frequencies centered at ω_0 . The other signals of equation 3-3 are attenuated. From the output characteristic curves, it was observed that the base current and collector current, for the transistors used (2n930, 2n2483, and 2n918), are linearly related. Thus, the base current ($i_b(t)$) is related to the collector current in equation 3-3 by a constant. This is shown in equation 3-6 and the new constants are denoted by K'

$$\begin{aligned}
 i_b(t) = & K'_1 V_{sm} \cos \omega_s t + K'_2 V_{om} \cos \omega_0 t + \frac{1}{2} K'_2 V_{sm}^2 (1 + \cos 2\omega_0 t) \\
 & + \frac{1}{2} K'_2 V_{om}^2 (1 + \cos 2\omega_s t) + K'_2 V_{sm} V_{om} \left[\cos (\omega_s + \omega_0)t + \right. \\
 & \left. \cos (\omega_s - \omega_0)t \right] \quad (3-6)
 \end{aligned}$$

Some components of the base and collector currents will have an effect on the circuit operation. The transistor is already modulated by ω_0 . Thus, this component will not add to the circuit output. With ω_s and ω_0 being within 10KHz in frequency, the components of current at $2\omega_s$, $2\omega_0$ and $\omega_s + \omega_0$ are too high in frequency to have any effect on the output signal. The component of current at ω_s will

have an effect on the output. The effect shows up in the strength of the side bands and will be discussed later. The D.C. components can be considered as part of the D.C. bias current.

The signal of interest is again the difference signal (ω_D). With the two original frequencies (ω_s and ω_o) less than 10 KHz apart, the difference frequency is much less than the carrier frequency. In the case of the transmitter in Fig. 2-3, the carrier frequency is 380 KHz. Thus, the difference signal is of a low enough frequency to modulate the output signal.

D. Amplitude Modulation

Amplitude modulation can be obtained by a number of methods. One method is to change the amplitude of the oscillations of a carrier frequency oscillator by changing its operating point at the modulation frequency. This method can be implemented by changing the emitter bias current. The analysis of the amplitude modulated oscillator is similar to that of the amplitude modulated amplifier¹³. Thus, the modulation circuit can be analyzed using the circuit in Fig. 3-5.

In Fig. 3-5, the base source current is given by equation 3-6. Although most of the components are of too high a frequency to modulate the carrier, they will be considered. The components of current at $2\omega_o$, $2\omega_s$ and $\omega_s + \omega_o$ will be attenuated. At these frequencies, the input impedance to the crystal oscillator stage is approximately one half the value that it is at the crystal

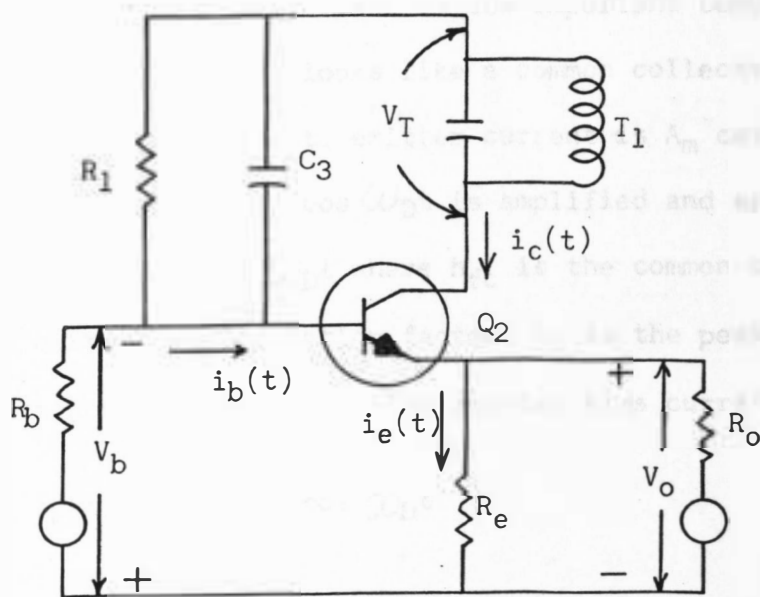


Fig. 3-5. Equivalent Modulation Circuit.

frequency (ω_0). The current at ω_s will affect the circuit, and will be discussed later. This leaves the D.C. component and the ω_D component of the base circuit.

The collector current contains all the components of equation 3-3. However, the collector voltage $V_T(t)$ can only exist within a narrow band of frequencies centered at ω_0 . The collector voltage (V_T) will be

$$V_T(t) = V_{Tm} \cos \omega_0 t \quad (3-7)$$

With the current input, no further mixing will occur because of the linear relationship between i_b and i_c . Thus, the difference frequency component of the base current is the important component. To the ω_D component the circuit looks like a common collector stage. With $A_m = K_2 V_{sm} V_{om}$, the base to emitter current is $A_m \cos \omega_D t$.

The modulating signal $A_m \cos \omega_D t$ is amplified and appears in the emitter circuit as $h_{fc} A_m \cos \omega_D t$ where h_{fc} is the common collector short circuit current amplification factor, A_m is the peak amplitude of the modulation signal current. The emitter bias current is

$$i_E(t) = I_0 + K' \cos \omega_D t \quad (3-8)$$

$$K' = h_{fc} A_m$$

and I_0 is the emitter D.C. bias current.

The gain of the transistor stage is highly dependent upon total emitter current⁶. The voltage amplification A_V can be approximated by⁶

$$A_V(t) = K'' i_E(t) \quad (3-9)$$

where K'' is a constant dependent upon the device. The voltage amplification is

$$A_V(t) = K''(I_0 + K' \cos \omega_D t) \quad (3-10)$$

The output voltage is given by

$$V_{out}(t) = A_V V_T(t) \quad (3-11)$$

Substitution of equation (3-7) and (3-10) into equation (3-11) yields

$$V_{out}(t) = K''(I_0 + K' \cos \omega_D t)(V_{Tm} \cos \omega_0 t) \quad (3-12)$$

Equation (3-12) may be written as

$$\begin{aligned} V_{out}(t) &= K'' I_0 V_{Tm} \cos \omega_0 t + \frac{1}{2} K'' K' V_{Tm} \cos (\omega_0 + \omega_D)t \\ &\quad + \frac{1}{2} K'' K' V_{Tm} \cos (\omega_0 - \omega_D)t \\ V_{out}(t) &= K \left\{ V_{Tm} \cos \omega_0 t + \frac{1}{2} (m_a V_{Tm}) \left[\cos (\omega_0 + \omega_D)t \right. \right. \\ &\quad \left. \left. + \cos (\omega_0 - \omega_D)t \right] \right\} \quad (3-13) \end{aligned}$$

where $K = K'' I_0$ and the modulating factor is

$$m_a = \frac{K'}{I_0} .$$

Equation (3-13) represents amplitude modulation and the output signal shown in Fig. 3-6a. Because of the approximation made in equation (3-9), equation (3-13) is free of unwanted signals or harmonics. This is not normally the case. However, the output equation 3-13 is a good estimate of the actual signal as can be seen in Fig. 3-6a,b. The unwanted signals are filtered out by the collector circuit.

Fig. 3-6b is a picture of the frequency spectrum of the output signal. The picture is a reflection of the actual spectrum with frequency increasing to the left. From the picture one can see that the upper sideband is stronger than the lower sideband.

The fact that the upper sideband is stronger is due to the nature of the current input to the base $i_b(t)$. It should be noted that the $(\omega_0 + \omega_D)$ sideband is equal to ω_s , if ω_s is greater than ω_0 , and the $(\omega_0 - \omega_D)$ sideband is equal to ω_s , if ω_s is less than ω_0 . Since ω_s is so close to the filter frequency, it is amplified and thus adds power to the upper sideband. A possible reason for this will be discussed in Chapter IV.

In the circuit designed, the filter is inherently set to the crystal frequency because it is part of the oscillator circuit. However, if an amplifier is actually used with two voltage inputs as in Fig. 3-3, the tank circuit can be tuned to any one of the higher frequencies of $i_c(t)$ (equation 3-3). The output of this circuit is a signal at the frequency of the tank circuit modulated by the

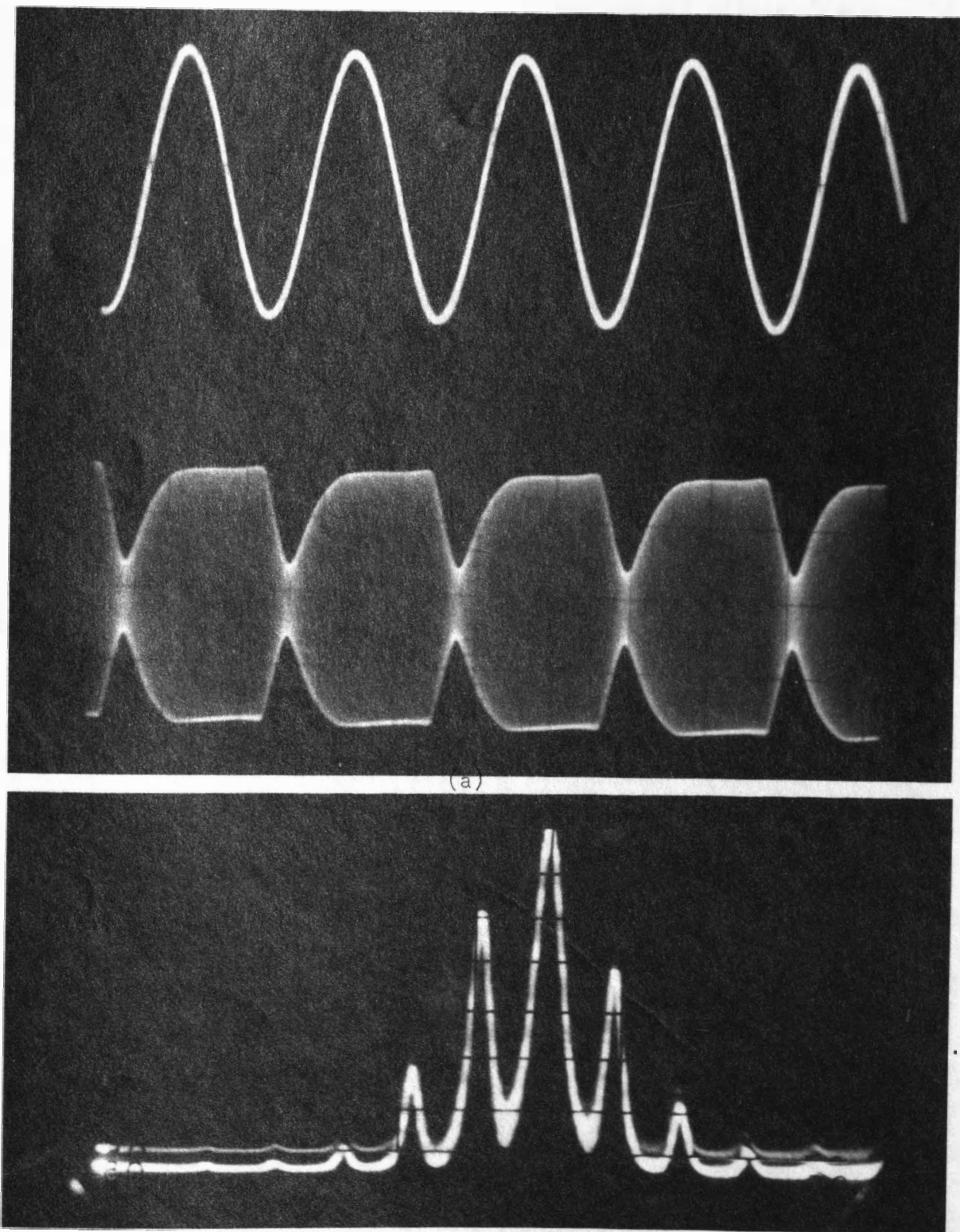


Fig. 3-6. (a) Output Signal After and Before Demodulation.
(b) Frequency Spectrum.

difference frequency. For example let the tank be tuned to $2\omega_0$, then the output will be

$$V_{\text{out}}(t) = K \left\{ V_{\text{Tm}} \cos 2\omega_0 t + \frac{1}{2}(m_a V_{\text{Tm}}) \left[\cos(2\omega_0 + \omega_D)t + \cos(2\omega_0 - \omega_D)t \right] \right\} \quad (3-14)$$

Equation 3-14 was obtained by substituting $2\omega_0$ in equation 3-13.

This idea will be demonstrated experimentally in Chapter IV.

In the analysis of the circuit there are various other factors such as percent modulation versus temperature or input voltages, frequency stability versus temperature and the filtering ability of the feedback network.

CHAPTER IV

EXPERIMENTAL DATA AND DISCUSSION OF RESULTS

In this chapter, a number of features of the FM/AM circuit will be discussed. First, the collector filter circuit that was assumed, in Chapter III, will be discussed. Second, in Chapter III, the observation was made that any one of the frequency components of the collector current could be picked off as the carrier frequency. The carrier frequency would still be modulated by the difference frequency. This will be demonstrated. Third, the percent modulation of the output signal will be discussed. Fourth, the temperature stability of the system is discussed.

All of the experimental data shown in this chapter was gathered with 2n930 type transistors in the circuit. Although three different transistors were used (2n930, 2n2483 and 2n918), the 2n930 was typical of the three. Also, it was noted that the circuit operation was much better when the sensing oscillator was tuned above the crystal oscillator frequency. This will be discussed later in this chapter and the data were taken with the sensing oscillator frequency above the crystal oscillator frequency.

A. Collector Filter Circuit

In determining an appropriate model of the FM/AM system, the collector circuit load was considered to be a tuned filter. Because the filter was part of the oscillator circuit, the tuned frequency was 380 KHz. To test the selectivity of the filter, the crystal

oscillator feedback loop was broken as shown in Fig. 4-1. The curve in Fig. 4-2 was plotted from data taken with the output voltage (V) as a function of the input frequency (ω_s). The source voltage (V_s) was maintained at a constant amplitude.

The curve in Fig. 4-2 shows that the circuit amplification is not symmetrical about the crystal frequency. The signals with frequencies 5KHz above the crystal frequency are amplified more than those signals whose frequencies are 5KHz below the center frequency. Thus, the unsymmetrical amplification is a possible explanation for better circuit operation with the sensing oscillator tuned above the crystal oscillator.

Fig. 4-2 can also be used in analyzing the unsymmetrical frequency spectrum of the transmitter shown in Fig. 3-6b. With the sensing oscillator tuned above the crystal oscillator, the transmitter upper sideband contains more power than its lower sideband. The frequency of the sensing oscillator is equal to the upper sideband frequency. Thus, the signal is amplified and adds power to the upper sideband.

The circuit shown in Fig. 4-1 was also used to verify that only the signal at the crystal frequency (ω_o) is fed back to the emitter of transistor (Q_2). Again the amplitude of the input voltage was held constant and the frequency was varied. The curve is a plot of feedback voltage (V_{fb}) versus the input frequency (ω_s). As can be seen in Fig. 4-3, the amount of voltage fed back is attenuated to the extent that it can be neglected except at the crystal frequency (380 KHz).

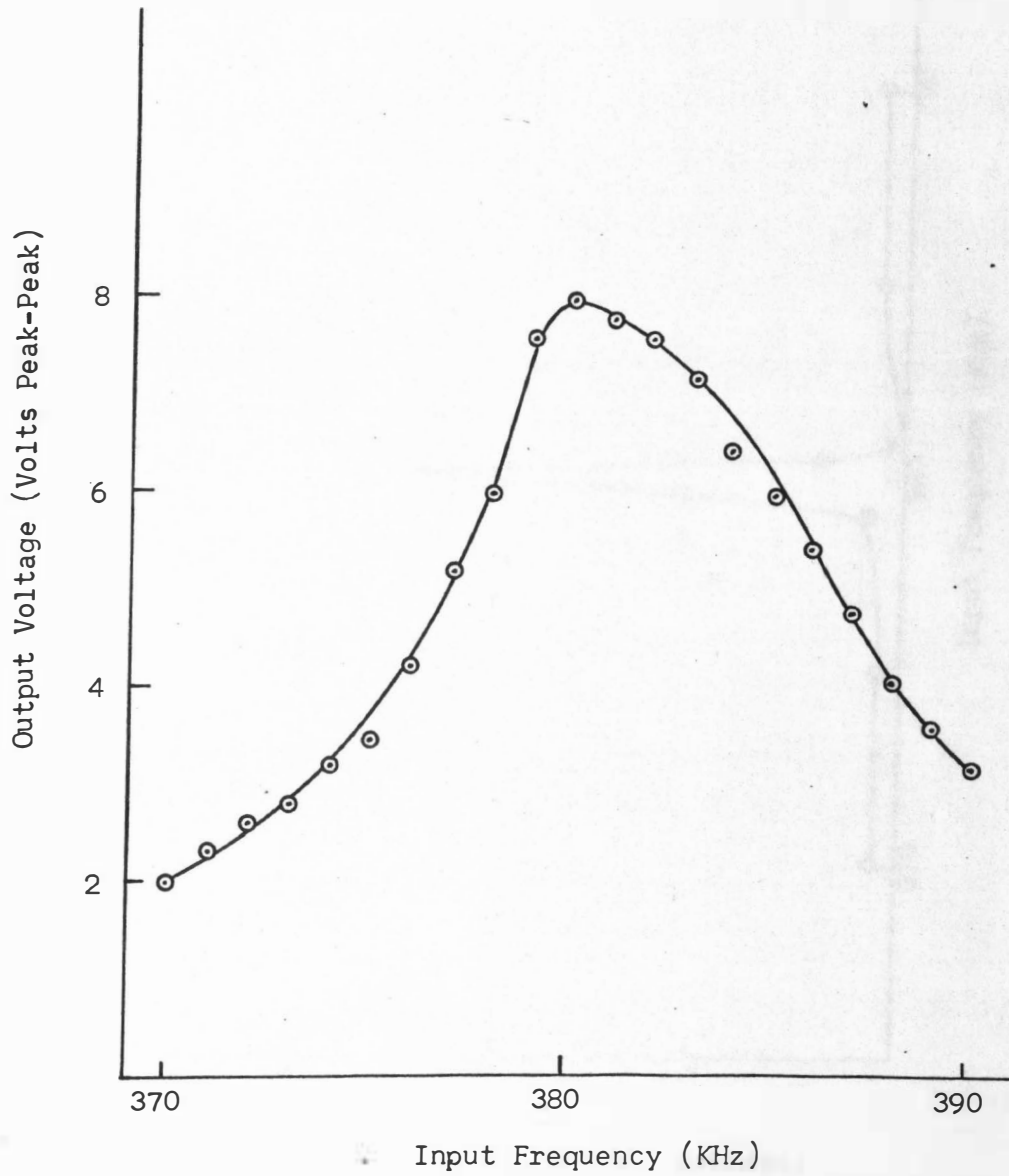


Fig. 4-2. Collector Filter Selectivity.

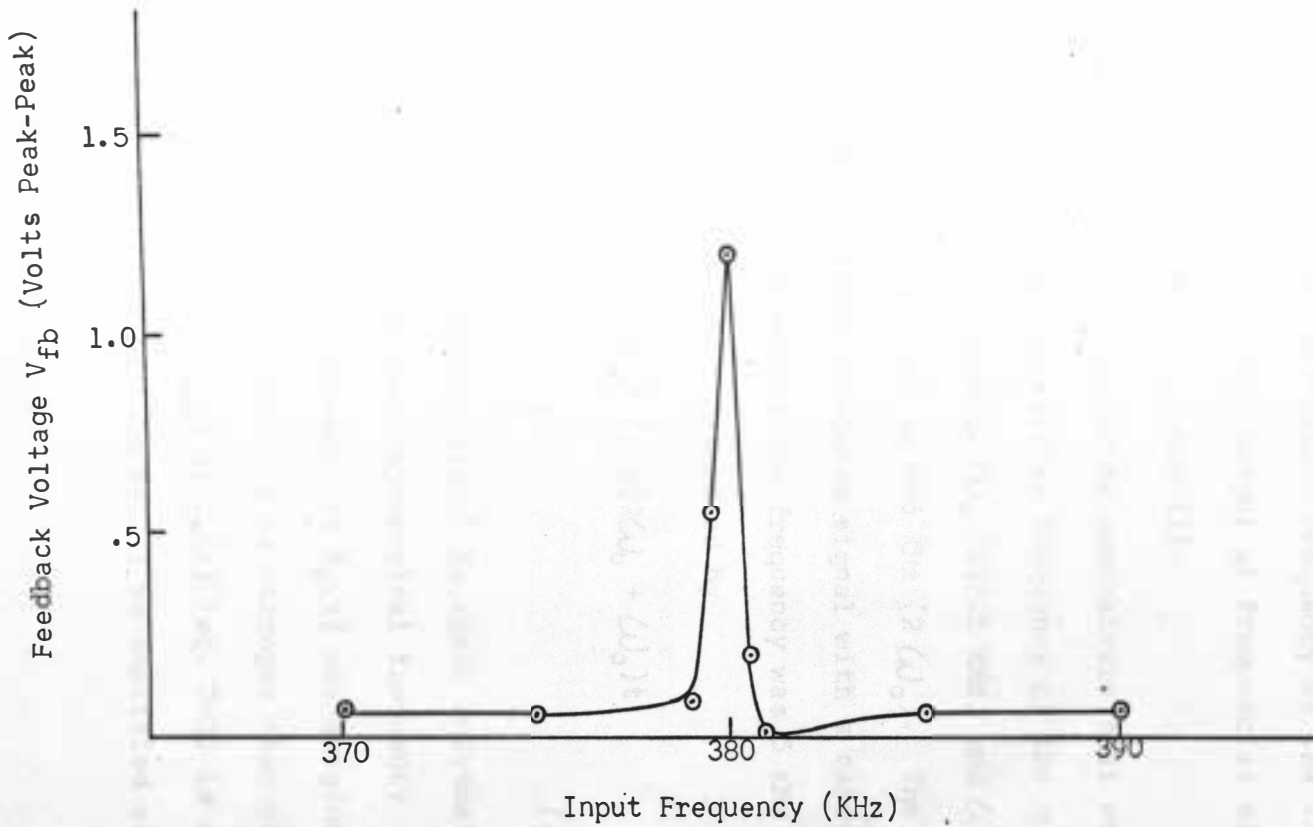


Fig. 4-3. Relative Feedback Voltage of Crystal Filter.

B. Second Harmonic Output

In the mixing circuit shown in Fig. 3-3, the tank circuit was tuned to the original emitter input frequency. The output was at that frequency and modulated by the difference frequency of the two inputs. The possibility of developing an output at frequencies different than ω_s and ω_o was suggested in Chapter III.

The circuit shown in Fig. 3-3 was used to demonstrate that other components of $i_c(t)$ can be used as the carrier frequency of the output signal. The two input frequencies were ω_s (232.5 KHz) and ω_o (227.5 KHz). The tank circuit was tuned to 455 KHz ($2\omega_o$). The output signal received was an amplitude modulated signal with a carrier frequency of 455 KHz ($2\omega_o$). The modulation frequency was 5 KHz ($\omega_s - \omega_o$). Thus, the output can be represented by

$$V_o(t) = K \left\{ V_{TM} \cos 2\omega_o t + \frac{1}{2}(M_a V_{TM}) \left[\cos(2\omega_o + \omega_o)t + \cos(2\omega_o - \omega_o)t \right] \right\} \quad (4-1)$$

The frequency spectrum of the output signal is again unsymmetrical. Equation 4-1 does not indicate the unsymmetrical frequency spectrum. However, the $(\omega_s + \omega_o)$ component of $i_b(t)$ was originally ignored as in Chapter III. The upper sideband is stronger than the lower sideband. The component $(\omega_s + \omega_o)$ of $i_b(t)$ (eq. 3-3) is equal to the upper sideband frequency. Thus, the signal is amplified and adds power to the upper sideband.

C. Percent Modulation

The percent modulation of the FM/AM system developed in Chapter II is a factor that has to be considered when constructing an operational unit. The percent modulation of the output signal varies with different circuit parameters and inputs.

The important or controlling variation is the variation in percent modulation with the frequency of the sensing oscillator. From the curve in Fig. 4-4 one observes that as the input frequency is decreased the percent modulation increases. An explanation for this goes back to Fig. 4-2. The closer the sensing frequency is to the tuned frequency, the more it is amplified. Thus, the percent modulation is increased.

The percent modulation also varies with the base and emitter voltages of transistor Q₂. In Fig. 4-5 and 4-6, percent modulation is plotted versus the input and feedback voltages. Fig. 4-5 is a plot of percent modulation versus the input voltage from the sensing oscillator with the feedback voltage maintained constant (.67 volts). In Fig. 4-5, curves are drawn for three different input frequencies. The curves in this figure show the significance of the amplification of the frequencies closer to the crystal frequency. With the difference frequency smaller, the percent modulation is greater and increases with a greater slope when the voltage is increased.

The curves in Fig. 4-6 are much the same as those in Fig. 4-5. Percent modulation is plotted versus feedback voltage. The sensing oscillator is again set at three different frequencies with the voltage

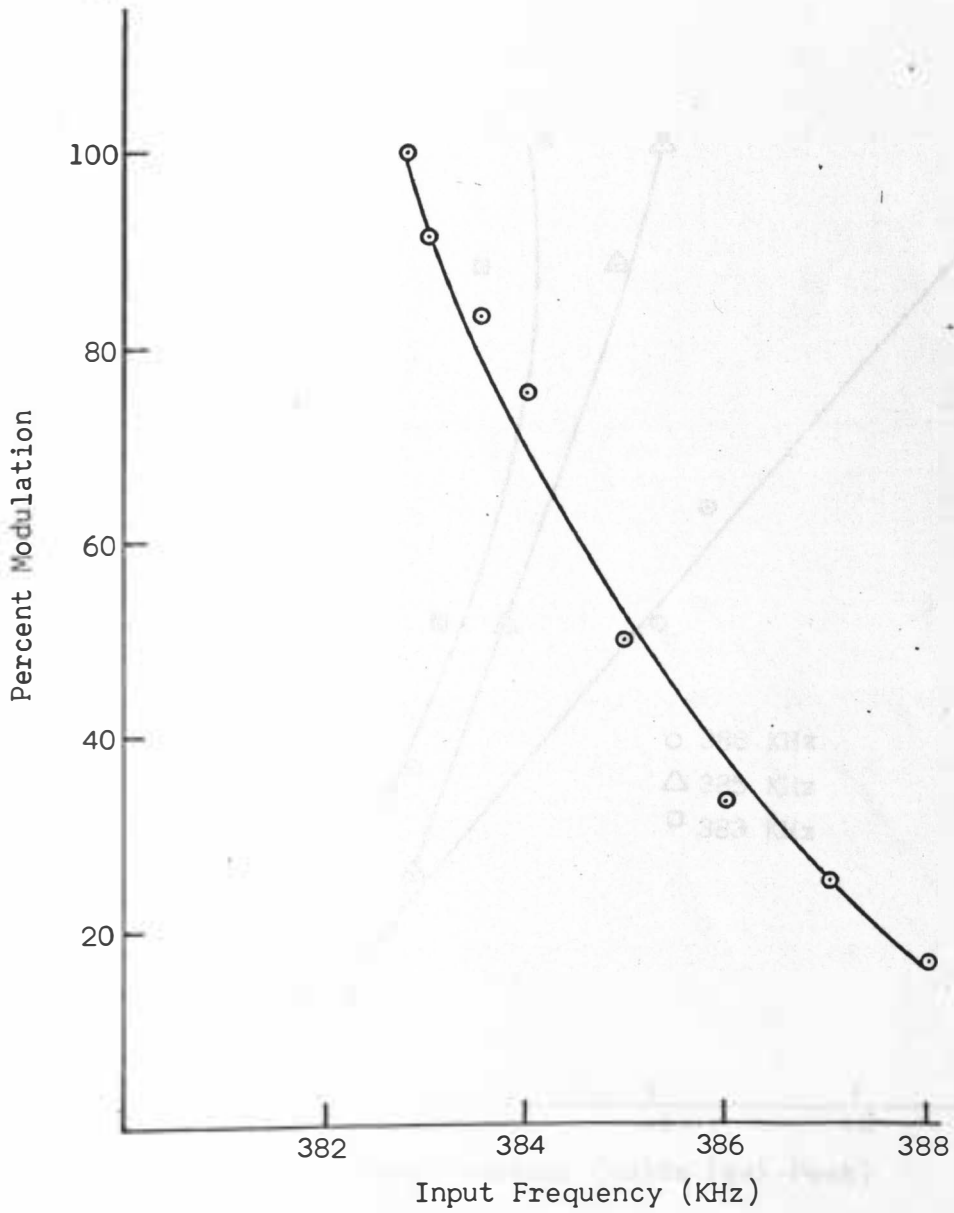


Fig. 4-4. Percent Modulation Versus Input Frequency.

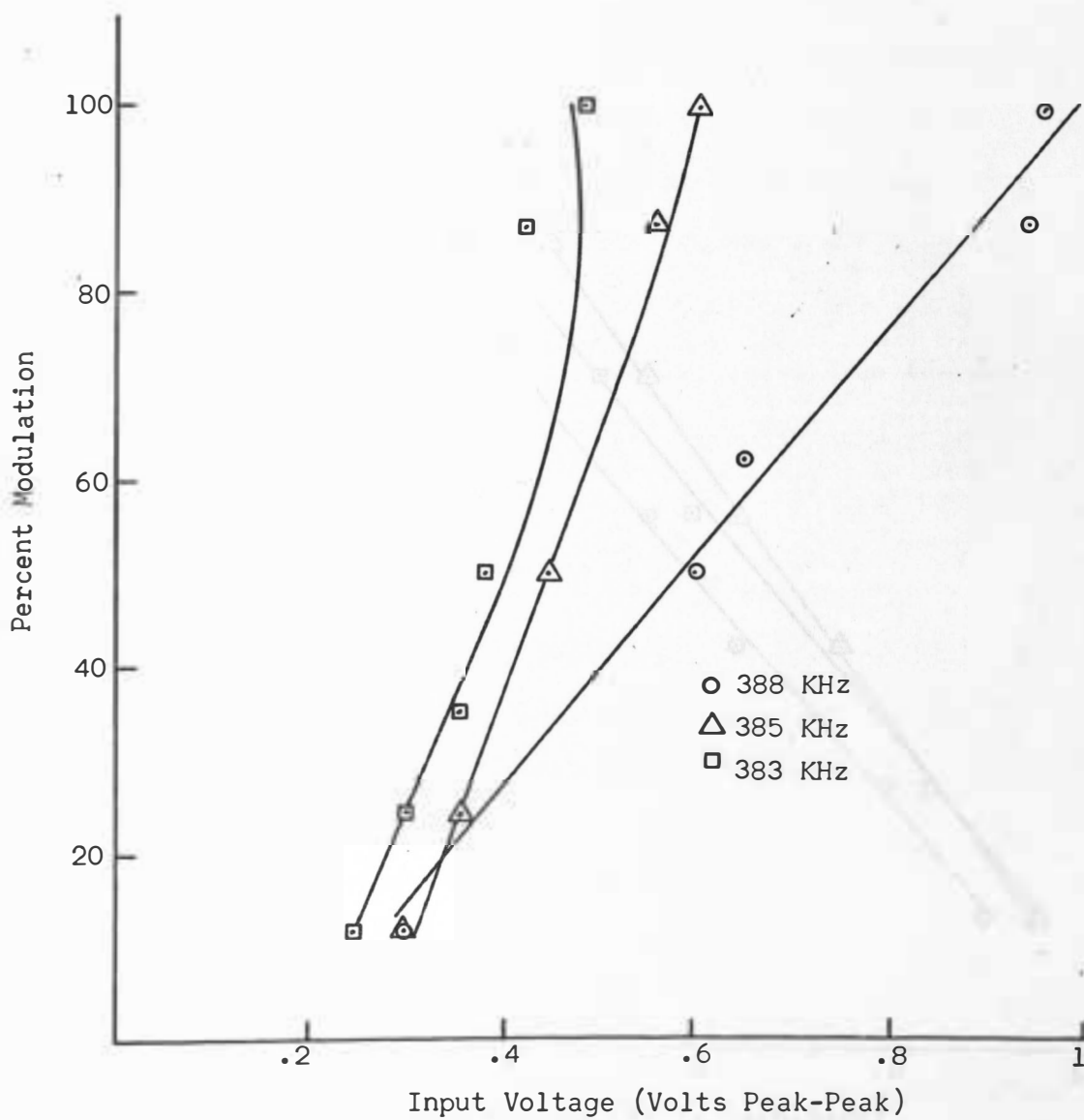


Fig. 4-5. Percent Modulation Versus Input Voltage.

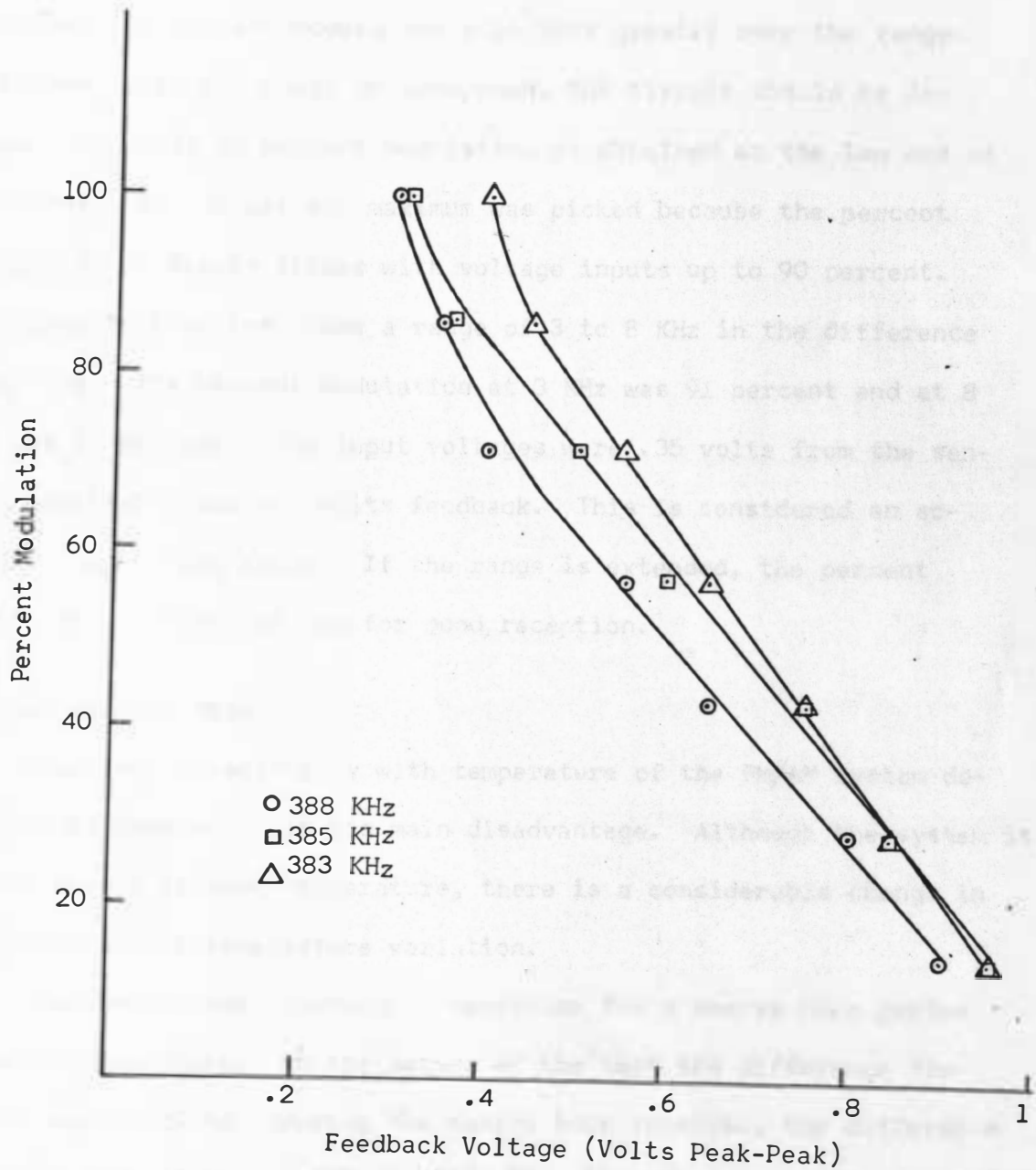


Fig. 4-6. Percent Modulation Versus Feedback Voltage.

maintained constant. Data from the two figures can be used to obtain proper modulation over the entire range of the difference frequency. With the difference frequency allowed to vary over the audio frequencies, the percent modulation will vary greatly over the range. Therefore, with the range decided upon, the circuit should be designed such that 90 percent modulation is obtained at the low end of the range. The 90 percent maximum was picked because the percent modulation is fairly linear with voltage inputs up to 90 percent. The curve in Fig. 4-4 shows a range of 3 to 8 KHz in the difference frequency. The percent modulation at 3 KHz was 91 percent and at 8 KHz was 17 percent. The input voltages were .35 volts from the sensing oscillator and .67 volts feedback. This is considered an acceptable operating range. If the range is extended, the percent modulation becomes too low for good reception.

D. Temperature Stability

Frequency instability with temperature of the FM/AM system developed in Chapter II is its main disadvantage. Although the system is fairly stable at room temperature, there is a considerable change in frequency with a temperature variation.

The circuit was observed in operation for a twelve hour period at room temperature. At the outset of the test the difference frequency was 4,624 Hz. During the twelve hour interval, the difference frequency varied from 4,600 to 4,630 Hz. In tests run on the crystal oscillator, the frequency variation was never over one Hz. Thus, the variation was in the sensing oscillator.

A frequency stability test was run under varying temperature conditions. The modulation or difference frequency was plotted, in Fig. 4-7, as the temperature was varied. The modulation frequency varied 377 Hz over the 40° range. This is a disadvantage if the system is used as a pressure sensing device. A change in the modulation frequency would then not necessarily mean a change in pressure. It could mean a change in temperature. If the system is used as a temperature sensing device, no problem would be realized. The temperature stability factor would be included in a calibration of the system.

A frequency stability test was then run on the individual oscillators. The crystal oscillator was subjected to an 80 to 120°F temperature range. The variation was 9 Hz from 399,990 at 120°F to 399,999 Hz at 80°F. Thus, the crystal was not causing the problem in the total system.

Fig. 4-8 shows the sensing oscillator, frequency stability test. The frequency of oscillation was 384,325 Hz at 120°F. When the temperature was lowered, the frequency of oscillation decreased to a low of 384,025 Hz at 90°F. This change was of the same order as the total system change.

The change in frequency of the sensing oscillator is a very small percentage of its initial value. The 300 Hz change is only 0.078 percent change from the initial value. However, this change has to be considered in the total system. In Fig. 4-7, the 377 Hz change is 7.55 percent change from the initial value. Thus, to improve the system, the stability of the sensing oscillator has to be improved.

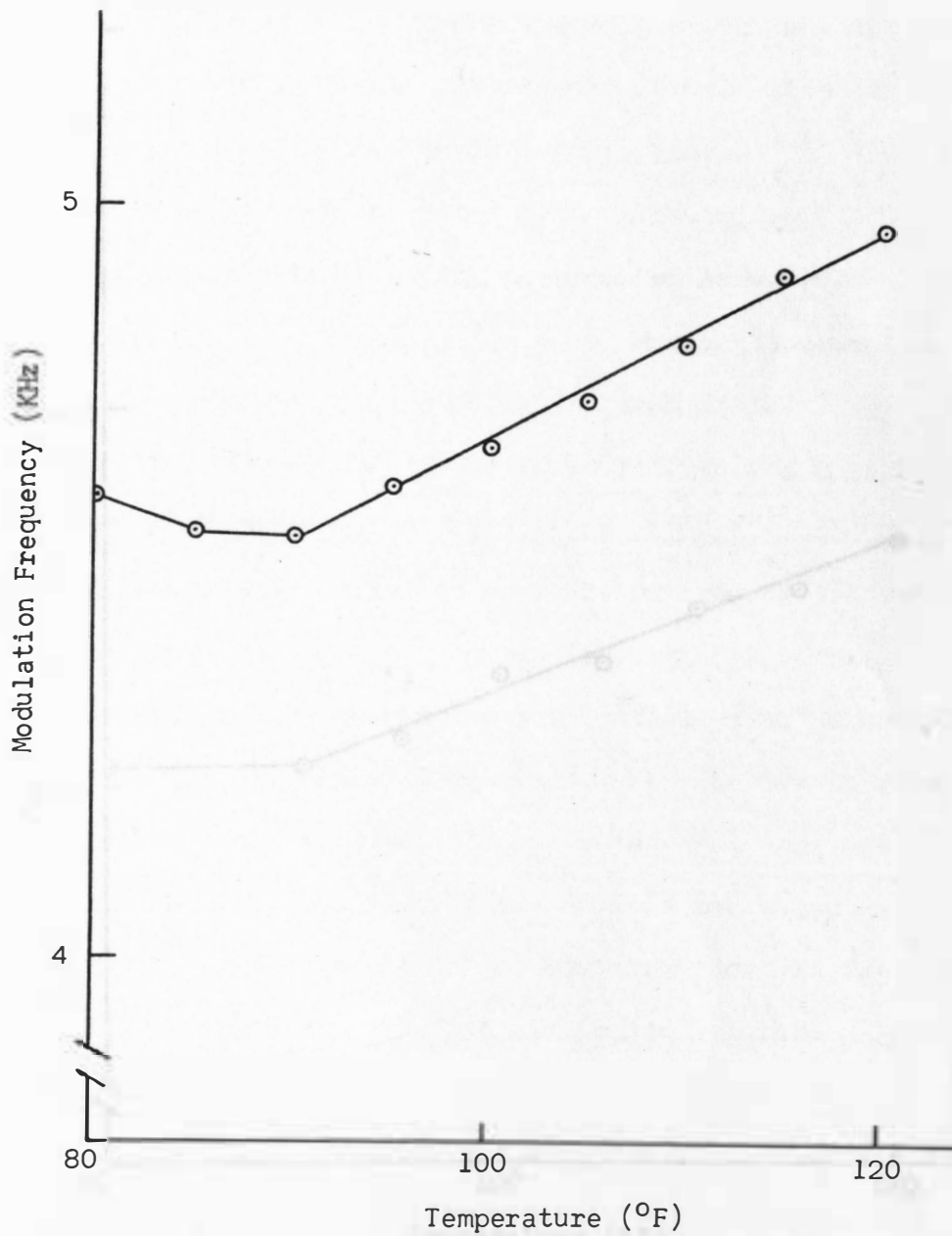


Fig. 4-7. Modulation Frequency Versus Temperature.

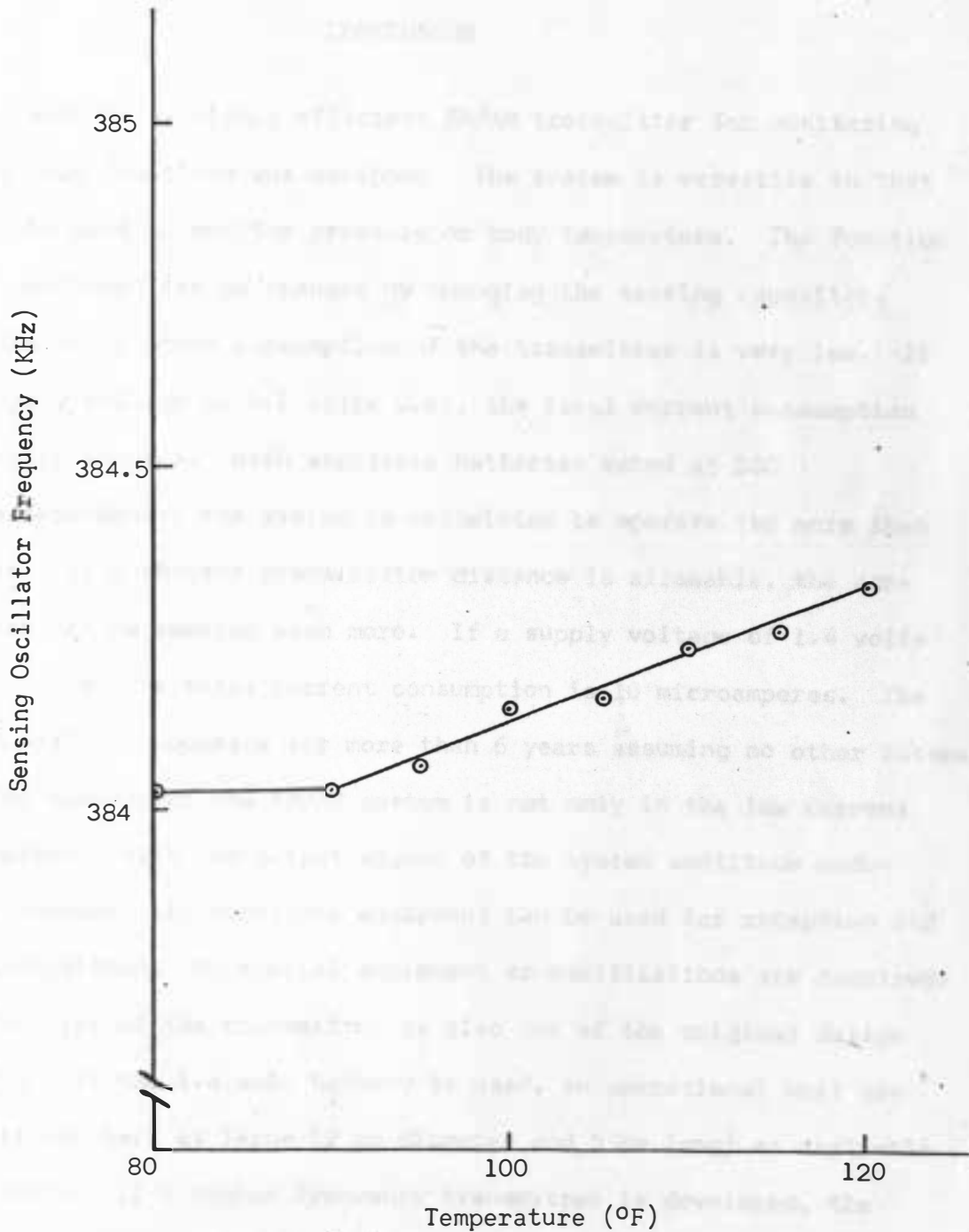


Fig. 4-8. Sensing Oscillation Frequency Versus Temperature.

CHAPTER V

CONCLUSION

A versatile, highly efficient FM/AM transmitter for monitoring animal body functions was designed. The system is versatile in that it can be used to monitor pressure or body temperature. The function to be monitored can be changed by changing the sensing capacitor.

The total power consumption of the transmitter is very low. If the supply voltage is 5.6 volts D.C., the total current consumption is 30 microamperes. With available batteries rated at 500 milliamperes-hours, the system is calculated to operate for more than 2 years. If a shorter transmission distance is allowable, the consumption can be reduced even more. If a supply voltage of 1.4 volts D.C. is used, the total current consumption is 10 microamperes. The system will then operate for more than 6 years assuming no other losses.

The economy of the FM/AM system is not only in the low current consumption. With the output signal of the system amplitude modulated, commercially available equipment can be used for reception and data acquisition. No special equipment or modifications are required.

The size of the transmitter is also one of the original design criteria. If the 1.4 volt battery is used, an operational unit can be built one half as large (2 cm diameter and 5 cm long) as available FM/AM units. If a higher frequency transmitter is developed, the unit will be even smaller because many of the circuit components will be reduced in size.

The percent modulation is fairly linear up to 90 percent modulation with the input voltages. However, the percent modulation varies with the frequency input. This must be considered when building an operational unit.

The main disadvantage of the transmitter is its frequency instability with a temperature change. A small change in the frequency of the sensing oscillator effects a large change in the modulation frequency.

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