FROM NATIONAL TELEMETERING CONFERENCE
LOS ANGELES, AUGUST 20-21, 1956
Published in National Telemetering Conference - 1956

TRANSISTORS APPLIED TO AN OPERATIONAL
FM-FM TELEMETRY SYSTEM

C. B. McCampbell, R. H. Gablehouse, P. R. Scheele, R. P. Matthews
Transmission Systems Division 5223
Sandia Corporation
Albuquerque, New Mexico

SUMMARY

This paper describes four basic components of an operational telemetry system. These components consist of a "Transistor Voltage Controlled Subcarrier Oscillator", which meets the RDB standards for subcarrier channels; a "Transistor Mixing Amplifier" which is used for impedance transformation and amplification of the mixed subcarrier signal; a "Transistor Current Controlled Subcarrier Oscillator" which also meets RDB standards and is capable of being deviated over the RDB limits directly from the output of a thermocouple at five microwatts; and finally a "Switching Transistor Converter" used for providing transmitter power at 185-volts, and 90 ma from a 28-volt source.

The basic circuit operating principles of the Voltage Controlled and Current Controlled oscillators are presented along with environmental test results. Circuit details of the Mixing Amplifier and Converter are not unique and are briefly mentioned. Some of the problems of parameter non-uniformity and parameter variation with temperature are discussed.

INTRODUCTION

Before going into the technical details of each of the components, a general description of the overall system will be given.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

The following pages are an exact
representation of what is in the original
document folder.

This basic system has been in operational use for ten months, during which time approximately twenty-five systems have been expended. The data obtained from the tests has been extremely reliable and consistent with little or no loss of information directly attributable to subcarrier oscillators. The conditions for operational expediency in relation to pre-flight adjustment were extremely severe. Due to the inaccessibility of the telemetry equipment, final adjustments were made two weeks before the test was held.

Despite the success of this equipment on this airborne type test and on high speed sled tests, it is still not to be considered an all-purpose system. The duration of the actual test or the actual time during which data is recorded is exceptionally short, being less than a minute. The system is closely calibrated just prior to initiating the test and with the given drift characteristics, there is little or no error introduced by changes in deviation sensitivity, linearity, and zero shift.

The Voltage Controlled Oscillator is deviable with either a zero to three-volt DC input, a plus or minus one and a half-volt DC input, or a three-volt peak-to-peak AC signal.

The permissible frequency of an applied AC signal is equal to and greater than the RDB standards. The input impedance is 200,000 ohms or more. All subcarrier outputs are mixed and the composite signal is amplified by a common emitter Mixing Amplifier with a common collector output stage. The output of the amplifier frequency modulates the transmitter in the normal fashion.

The Current Controlled Oscillator is the same physical size as the Voltage Controlled Oscillator and takes its input directly from a thermocouple. Its output is handled identically to the normal subcarrier oscillator

output. The technical details of this and the remaining three units follow.

A TRANSISTOR VOLTAGE CONTROLLED OSCILLATOR

The circuit for this oscillator may be separated into two basic parts; the emitter-coupled L-C oscillator, figure 1a and the variable reactance modulating stage figure 1b. The variable reactance stage draws a leading quadrature current and thus presents a capacitive reactance across the tank circuit of the oscillator. The nature of this capacitive reactance is developed as follows:

Figure 1c is the representative AC circuit of modulator while figure 1d is the equivalent circuit of the modulator represented by the familiar common base "h" parameters of the modulator transistor. The component R is a combination resistor-thermistor element used for temperature compensation.

Relating the current " i_t " and the voltage " v_c " an expression for the admittance of the stage is as shown in figure 2a. From the susceptance term then comes the expression for the equivalent capacitance presented by the modulator. This capacitance is a function of the transistor parameters which are a function of and are controlled by the emitter current. The emitter current is in turn controlled by the signal voltage applied to the base.

Figure 2b shows the variation of the $(1 + h_{21}K)$ term as a function of emitter current. The family of curves indicate in a heuristic manner the possibility of using the element R as a temperature compensating element.

Figure 2c is a logarithmic plot of the equivalent modulator capacitance

as a function of the emitter current. To obtain a linear "Input-Voltage Versus Frequency" calibration curve this should be a straight line. However, even though figure 2c is not precisely linear, the nonlinearity is cancelled by the normal nonlinearity of input voltage versus emitter current. The linearity of the calibration curve is within 5% of bandwidth provided the operating point is properly adjusted. Due to the nonuniformity of transistor parameters about 50% of the oscillators require the change of one fixed resistor to optimize linearity.

Figure 3 indicates the experimental results obtained from a typical oscillator which has been properly compensated. It can be seen that the changes in sensitivity, linearity, and zero shift are less than 5% of bandwidth.

After much experimentation with large samples of transistors, it was concluded that due to the nonuniformity in the variation of parameters with temperature, the procedure for determining the proper compensating network would always be an experimental and arduous task. Since operational procedures at Sandia are such that considerable external power is available up until the time a test is to begin, it was decided that external heating of the package which contains the oscillators would be the best expedient. Thus the package temperature is thermostatically maintained in the present case to $105^{\circ}\text{F} \pm 2^{\circ}$.

Figure 4 shows that the long term stability of a typical oscillator is quite good at a given ambient temperature. To attain this stability, it is necessary to select the modulator transistor, an experimental procedure which is quite simple to perform. Due to the physical nature of the emitter region, a matter not made a subject of this paper, excessive drift is experienced.

when the input level is changed from zero to 3-volts DC, increasing the dissipation of the transistor. With the new type physically constructed transistor now available from T.I., the rejection rate in the selection process has been reduced to 10%.

Since the package temperature is closely controlled and since a precise five-point calibration is applied to each voltage controlled oscillator channel, just prior to a test and since the duration of the test is short, the accuracy of the data is assured.

Figure 5 shows a schematic of the complete oscillator and a photograph of the complete plug-in unit. The total power input is 28-volt DC at 1 milliampere. The modulator transistor is a Texas Instruments 904 and the oscillator uses Texas Instruments 905's.

A TRANSISTOR CURRENT CONTROLLED OSCILLATOR

In the process of subminiaturization of equipment, it is most desirable to eliminate entire components such as converting amplifiers rather than merely reducing their size. With this circuit, it is possible to cause the required frequency deviation of a subcarrier oscillator directly from the output of a thermocouple or DC excited strain gage.

This discussion will be limited to the thermocouple application.

The basic principle of operation involves the well known concept of controlling the inductance of an inductor by controlling the permeability of its core. If the controlled inductance is in the tank circuit of an oscillator, the frequency of oscillation will be a function of the controlling signal. Figure 6 shows the familiar expression of inductance as a function of permeability. Permeability being the only variable, the inductance may

be considered to vary with magnetizing force as shown in the graph.

Refer now to figure 7 which shows the circuit diagram of the complete subcarrier oscillator. Since the controlled inductance (saturable reactor) is the heart of the circuit, the discussion will concentrate there.

All windings to the right of the indicated cores are oscillator windings. The windings to the left are control windings. Considering the oscillator windings first, the frequency determining tank circuit in the emitter of the transistor is a transformer with a tuned secondary. This permits the use of a smaller tuning capacitor. The third winding provides positive feedback to the base of the transistor.

In order that the control and oscillator windings be isolated, each half of each oscillator winding is wound on a separate core. The cores are then placed together with the proper orientation to cancel the flux linking the control windings as shown and the control windings are wound about both cores.

The first control winding to the left of the indicated cores is the bias winding. It establishes, along with the amplitude of the oscillator, the initial permeability and thus the initial inductance of the saturable reactor. With proper adjustment, this may be either the low or center frequency of any given channel. The signal or thermocouple winding then adds or subtracts additional magnetizing force to raise or lower the permeability in accordance with the particular channel requirements.

Admittedly, this is an extremely heuristic explanation in that quantitative data concerning the number of turns, linearity, hysteresis, and saturation are omitted.

Compensation for frequency drift is accomplished by AC negative feedback from the oscillator tank circuit to the base of the transistor.

The diode is biased sufficiently in the reverse direction to always be in the nonconducting state. The percentage feedback is controlled by the diode negative temperature characteristic which correlates with the rising gain of the transistor with increasing temperature. Since the permeability of the core is partially determined by oscillator amplitude, controlling the amplitude of oscillation with negative feedback allows the control of and compensation for the frequency changes of the oscillator as it is affected by ambient temperature changes.

Present oscillators are used in the same heated package as the voltage controlled oscillator and are compensated by the above method. The zero shift, linearity, and sensitivity change remain within 5% of bandwidth over a temperature range from 80° to 120°F.

The thermocouple output of 5 microwatts is developed across 20 ohms, the resistance of the signal winding. Calibration of the oscillator is accomplished by applying a known current in five discrete increments to the calibration winding. These current increments are then representative of the thermocouple output over the temperature range to be monitored.

The thermocouple reference junction is inside the heated package where its temperature is controlled to $\pm 2^\circ\text{F}$.

The oscillator uses a Raytheon 2N130 transistor and requires 28-volts DC at 1.5 ma. Figure 8 is a photograph of the plug-in unit.

A TRANSISTOR MIXING AMPLIFIER

The output of all subcarrier channels is resistively mixed.

The complex audio signal is impressed across a common resistor which is the input potentiometer of the mixing amplifier, figure 9. The amplifier

circuitry is quite conventional. The input is a common collector stage followed by two resistance coupled common emitter stages and a common collector output stage. The output impedance is approximately 10 K ohms. The unbypassed emitter bias resistors provide degeneration to stabilize the amplitude of the amplifier sufficiently for FM-FM requirements. Since all information has been transposed into the form of a frequency deviation, the absolute amplitude is less important than maintaining a uniform response and associated constant delay from 1 KC to 100 KC.

The voltage gain of the amplifier is at least 25 and total harmonic distortion less than 2% for input levels up to 80 millivolts RMS. At higher input levels excessive distortion will result due to clipping. Care must be taken in gain adjustment to prevent overdriving which results in intermodulation components.

The amplifier provides sufficient output to deviate the Bendix TXV-13 or the Raymond Rosen 840-b transmitters 100 KC with minimum clipping of the complex signal.

Figure 9 shows a schematic of the amplifier circuitry and a photograph of the plug-in unit. The unit is the same physical size and shape as the two aforementioned units, and is housed in the same temperature controlled package.

The unit uses Texas Instruments 903 transistors and requires power input of 28-volts DC at 4 ma.

TRANSISTOR DC TO DC CONVERTER

Figure 10 shows the schematic of a very conventional common collector converter circuit which provides 185-volts DC at 90 ma for transmitter power. Since the circuit operating details are quite widely known,

only the circuit constants will be given. The transistors are Minneapolis-Honeywell type H-2. The toroid core is a Deltamax 4635. The windings are as follows:

Primary:	Emitter	- 120 turns center tapped
	Base	- 160 turns center tapped
Secondary:	400 turns	

The starting resistor is 10 K ohms and the base-bias resistor is 100 ohms. The diodes are automatic electric type 1B443.

Figure 11 is a photograph of the finished unit. When mounted on a suitable heat sink, it may be operated satisfactorily over an ambient temperature range from -10°F to 145°F .

CONCLUSIONS

Figure 12 is a photograph of a twelve-channel FM-FM system. The temperature controlled oscillator packages accommodate the voltage controlled oscillator, current controlled oscillator and mixing amplifier described herein. In addition, they accommodate the strain gage oscillators, the vibration calibration oscillators, and transistor vibrotron amplifiers to accompany the Byron-Jackson "vibrating wire" type transducer.

The packages as shown are usually directly wired into the system signal junction box which is a unit of arbitrary size and shape. This is the reason for omitting it from the photograph.

The subcarrier oscillators, both voltage controlled and current controlled and mixing amplifier, while in the containing packages, have been subjected to 500 g. shocks in the plane perpendicular to the base without noticeable deviation as noted at the output of the associated discriminators. These shocks were of 2 milliseconds rise time and 2 milliseconds

duration.

At 1,000 g's acceleration in the same plane, short duration spikes occurred on the record but no permanent deviations took place.

Heaters of approximately 60-watts capacity are required to maintain the package temperature at 105°F in still-air ambients down to -10°F.

To conclude, the hardware described herein speaks for itself in the data recorded on past tests. While the system requires some additional work to make it reliably stable enough to be used on longer duration tests, it is quite adequate for 60-second duration testing.

a. EMITTER COUPLED OSCILLATOR

* RESISTOR-THERMISTOR COMBINATION

c. AC CIRCUIT OF MODULATOR

b. VARIABLE REACTANCE MODULATOR

* COMMON BASE PARAMETERS

d. EQUIVALENT CIRCUIT OF MODULATOR STAGE

FIGURE 1.

$$g = \frac{R' (1 + h_{21} k)}{X_C} + h_{22}$$

$$R' = \frac{R h_{11}}{R + h_{11}} \quad k = \frac{R}{R + h_{11}}$$

$$jb = j\omega C (1 + h_{21} k)$$

$$C_{eq} = C (1 + h_{21} k)$$

a. THEORETICAL ANALYSIS OF
VARIABLE REACTANCE STAGE

b. THEORETICAL DATA SHOWING THE EFFECT OF
OF VARYING R IN COMPENSATING FOR
CHANGES IN TEMPERATURE

c. COMPARISON OF EXPERIMENTAL AND
THEORETICAL DATA

FIGURE 2.

FIGURE 5

$$L = \frac{3.19 N^2 \mu A}{\rho} \times 10^{-8} \text{ Hy's}$$

N - NUMBER OF TURNS
A - CROSS SECTIONAL AREA - IN²
ρ - LENGTH OF MEAN PATH - IN
μ - RELATIVE PERMEABILITY

PERMEABILITY
 VS
 MAGNETIZING FORCE

FIGURE 6

TCCO - T
 TRANSISTOR CURRENT-CONTROLLED OSCILLATOR
 -TEMPERATURE-

FIGURE 7

FIGURE 8

FIGURE 5

TRANSISTOR POWER SUPPLY

INPUT 28 VDC
 OUTPUT 185 VDC
 90 MA

FIGURE 10

FIGURE 11

FIGURE 12