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Pilotless aircraft telemetry

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PILOTLESS AIRCRAFT TELEMETRY

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F. S. Knight.

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PILOTLESS AIRCRAFT TELEMETRY

by

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PREFACE

The purpose of this paper is to provide a fundamental introduction to the process of telemetering. Although the subject of the paper is limited to pilotless aircraft and guided missile applications, the limitation is not a great one because it is this field which has produced most of the telemetering techniques now in use. It is hoped that a study of the following pages will enable the reader to better understand and evaluate any particular telemetering system he may encounter.

The paper was written in the main part during the third year of the electronics engineering curriculum at the U. S. Naval Postgraduate School. Much information and experience useful in the writing of the paper was gained during the writer's eleven-week working visit in the Electronics Department of the Glenn L. Martin Company at Middle River, Maryland.

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I. INTRODUCTION

Telemetering is the process of measuring the value of a quantity, transmitting this information to a distant station, and there indicating, recording, or integrating the value of the quantity measured. The art of telemetering was fostered by the growing complexity of interconnected electrical systems and remotely controlled power plants. Its early use was confined principally to electrical power applications in which wires were used as the transmission medium. Telemetering employing wireless transmission was first developed for use in meteorological services and for use in aeronautical test flights in which personnel were unable to keep adequate records of flight information, or in which valuable test data might be destroyed in the crash of the comparatively unimportant test model.

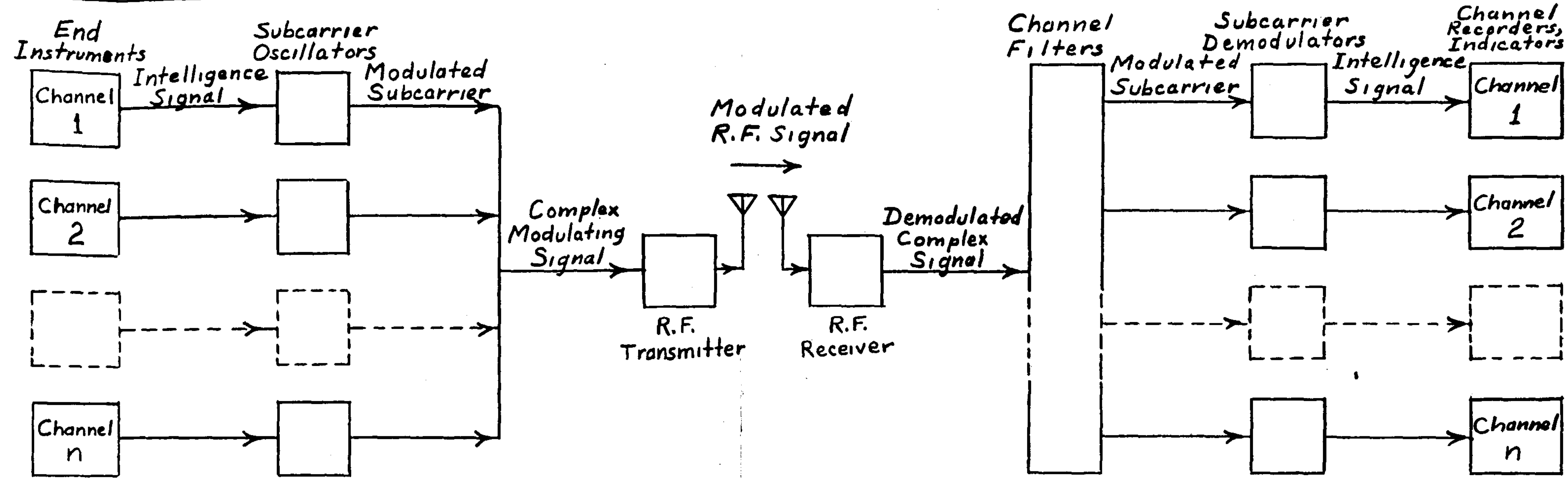
The advent of high speed missiles of the pilotless aircraft type introduced new and stringent requirements for telemetering equipment. The vital nature of the functions performed has demanded the fulfillment of these requirements. The resultant work and investigation, making use of the latest electronic developments and techniques, has achieved gratifying advances in a previously neglected art. However, progress was made in a rather unorganized manner. As a missile reached the stage at which telemetering was required, the group developing the missile would work out a system fulfilling its particular needs. The repetition of this sequence of events in many laboratories throughout the country was a duplication of expensive effort. Much good came of the situation, however, in that the many different methods of attack used by groups working independently of each other resulted in a wide variety of solutions to most telemetering problems. It is a treatment of these various solutions, rather than a study of any single telemetering system, that is the purpose of this paper.

As applied in pilotless aircraft, hereafter designated P/A, the telemetering process may be considered to involve the following phases: (1) measurement of the desired quantity, (2) transformation of the measurement energy into electrical energy, (3) modulation of a radio frequency carrier, (4) transmission and reception of the modulated carrier, (5) decoding, indication, and recording of intelligence resulting from demodulation , and (6) comparison of recorded information with the original measured quantity. The treatment of the requirements, problems, and methods of performing these functions of telemetering will be clarified by first giving an example of an application of telemetering.

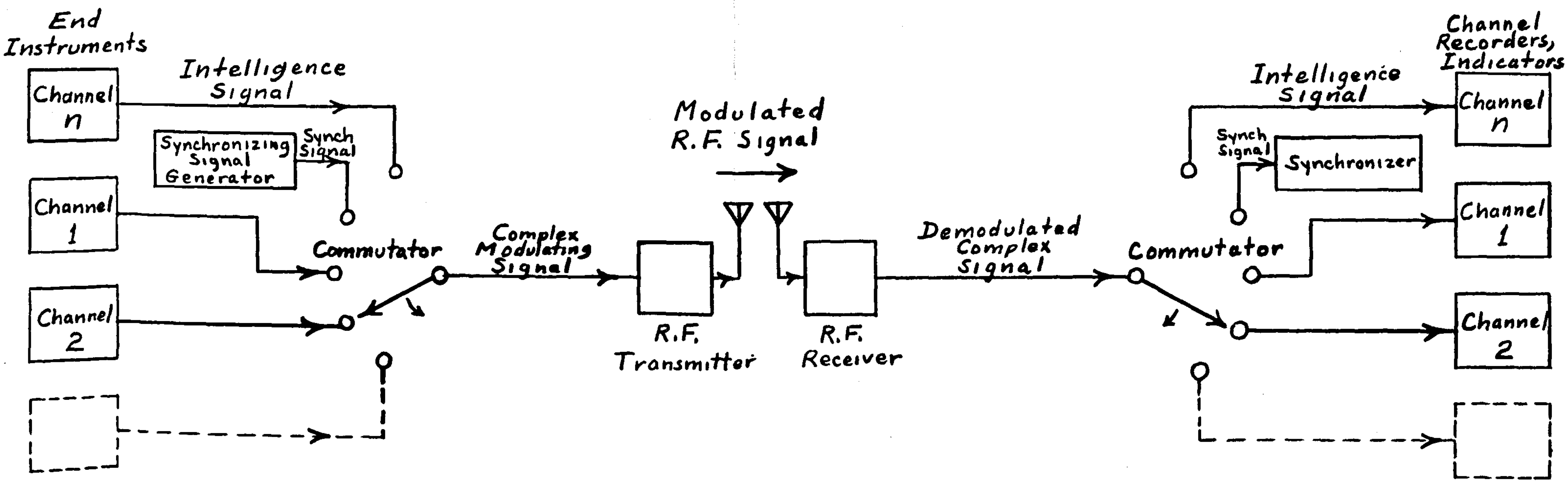
Suppose that in the flight testing of a pilotless aircraft it is desirable to obtain a record of combustion chamber pressure. First a pressure measuring instrument whose reading can be converted into an electrical signal is required. This audio signal is used to modulate a radio frequency carrier which is then transmitted to the remote receiving and recording station. The remote equipment must receive and demodulate the RF signal, and deliver an audio signal capable of driving a recording device that will present the intelligence in the desired form. The relationship of the remotely recorded information to the measured quantity, fuel chamber pressure in this case, is obtained and maintained by calibration previous to flight and by reference information transmitted during flight. Since, in the P/A application, it is desired to telemeter a number of quantities, a multiplex system is indicated. Thus, in the foregoing breakdown of the process, there is required in the airborne equipment a means of combining or synthesizing the various intelligence signals, and in the remote (ground) equipment a means of separating these signals back into their proper channels.

The principal phases of the telemetering process are shown in the block diagrams of Figure 1. The general practice of classifying a system by the type of multiplex employed was followed. Figure 1 (a) shows the functions performed in a system employing subcarrier (frequency sharing) multiplex and Figure 1 (b) those performed when commutation (time sharing) multiplex is used.

In the subcarrier system, the information to be telemetered modulates an audio frequency sinusoidal signal,



(a) SUBCARRIER TELEMETERING SYSTEM OF n CHANNELS - BLOCK DIAGRAM



(b) COMMUTATION TELEMETERING SYSTEM OF n CHANNELS - BLOCK DIAGRAM

FIGURE 1

there being one such subcarrier for each quantity to be measured. The modulated subcarriers are synthesized into a single signal which modulates the radio frequency carrier. After demodulation of the radio frequency carrier in the remote station receiver, the subcarriers are separated by band pass filters and the intelligence of each channel recovered by demodulation of its subcarrier. In this type of system each channel is thus identified by the frequency of its subcarrier.

In the commutation multiplex, the intelligence from each channel is successively sampled by a mechanical or electronic commutator, or by some form of counting chain or delay line. Each sample then modulates the radio frequency carrier during its portion of the commutation period. In the remote station the carrier is demodulated and the resulting complex signal is divided into the individual channel signals by a commutator which is synchronized with the airborne commutator.

Additional flexibility may be obtained by use of combinations of the two basic types of systems. For example, many systems in present use employ a subcarrier system in which one or more subcarriers are commutated among a number of subchannels. A system might also employ several groups of subcarriers, each group being synthesized into a single higher frequency subcarrier, and these higher subcarriers then commutated to modulate the radio frequency carrier.

Many other combinations are possible, but it will be seen that frequency response, band width, and other factors limit such applications.

Another method of telemetering information is by use of a television system. Although television systems have been employed successfully in telemetering, their use in pilotless aircraft is undesirable because their application is limited principally to conventional, direct reading instruments. Also, the equipment is expensive, complex, and large, and excessive bandwidth is required. In conventional telemetering systems, the desired information is the only consumer of bandwidth. In television systems, the desired information, that portion of the picture showing the reading of the instrument, represents only a small part of the total picture transmitted. The remainder of the picture conveys no pertinent information and thus represents a great waste of bandwidth.

In the pages that follow, the various telemetering functions are considered, in much the same order as they appear in Figure 1, as to the problems involved and some of the methods which have been developed to solve these problems. It must be remembered that what is an ideal solution for measuring a certain type of variable in one aircraft may be far from the best solution in another. Also, in applying the best possible solution to a given telemetering problem, a great deal of difficulty might be encountered, and usually is, not only electrically and electronically, but mechanically as well. In this comparatively new but fast-growing field, standard equipment and techniques are often not applicable.

II. GENERATION OF THE MODULATION SIGNAL

The generation of a signal containing the intelligence with which it is desired to modulate the radio frequency carrier comprises the first two steps mentioned in the foregoing breakdown of the telemetering process, i.e. (1) the measurement of the desired quantity and (2) the transformation of the energy of measurement into electrical energy as an intelligence signal in such a form that it is capable of modulating the radio frequency carrier in the desired manner. Before going into the generation of this signal, it is desirable to consider the types of information to be telemetered in P/A studies.

1. Information

Douglas [6] divides the testing of pilotless aircraft into three flight phases and defines them in the following manner:

> The launching phase- the initial phase of the flight from the start of the firing sequence until the period of normal stabilized flight has been achieved.
> The cruising phase- the flight period between launching and attack, including climbing, maneuvering, and traversing the distance to the target area.
> The attack phase- the terminating portion of the flight from the moment the P/A is explicitly directed towards the target until it is expended in the completion of its mission.

The suggested basic data measurements, arranged according to flight phase, for use in analysis of the performance of pilotless aircraft are listed in Douglas [6] as follows:

Launching Phase
- Aerodynamics:
  - Roll displacement, rate, and acceleration
  - Pitch displacement, rate, and acceleration

Yaw displacement, rate, and acceleration
Longitudinal acceleration
Altitude
Velocity
Temperature, outside air

Power Plant:
Combustion chamber pressure
Booster burning starting time (if multiple tube)
Booster burn-out time (if multiple tube)

Control and Guidance:
Control surface position and forces
Input signal to servo system
Gyro position

Accessory:
Voltage of electrical system

Structure:
Stress
Vibration

Cruising Phase

Aerodynamics:
Roll displacement, rate, and acceleration
Pitch displacement, rate, and acceleration
Yaw displacement, rate, and acceleration
Accelerations: longitudinal, lateral, and vertical
Altitude
Velocity
Temperature, outside air
Hinge moments
Angle of attack and yaw
Control surface positions, rates, and forces

Power Plant:
Combustion chamber pressure
Combustion chamber gas temperature
Fuel flow and quantity
Pump outlet pressure
Pump revolutions per minute
Tank pressures
Fuel nozzle or injection pressure
Combustion chamber wall temperature
Thrust

Additional for ram jets
Ram pressure
Ram temperature

Additional for pulse jets
Ram pressure
Ram temperature
Ram pressure upstream of vanes
Air temperature downstream of vanes

- Additional for turbo jets
  - Ram pressure
  - Ram temperature
  - Turbo revolutions per minute
  - Tailpipe temperature of gas
- Control and Guidance:
  - Input signal to servo system
  - Received signal strength
- Accessory:
  - Generator output current
  - System voltage
  - Compartment temperature
  - Accessory equipment operation
- Structure:
  - Stress
  - Temperature, critical structure
  - Vibration

Attack and Homing Phase

- Aerodynamics:
  - Roll displacement, rate, and acceleration
  - Pitch displacement, rate, and acceleration
  - Yaw displacement, rate, and acceleration
  - Accelerations: longitudinal, lateral, and vertical
  - Altitude
  - Velocity
  - Temperature, outside air
  - Angle of attack and yaw
  - Control surface positions, rates, and forces
- Power Plant:
  - Fuel flow and quantity
  - Combustion chamber pressure
  - Combustion chamber temperature
  - Thrust
- Control and Guidance:
  - Input signal to servo system
  - Seeker head position (if movable)
  - Seeker output signal
  - Received signal strength
- Accessory:
  - Arming signal
  - Detonation
  - System voltage
- Structure:
  - Stress
- Hydrodynamics: (underwater missiles)
  - Depth
  - Control surface positions, rates, and forces
  - Roll displacement, rate, and acceleration
  - Pitch displacement, rate, and acceleration
  - Yaw displacement, rate, and acceleration
  - Accelerations: longitudinal, lateral, and vertical
  - Velocity

2. Instruments

The preceding multitude of measurements may be resolved into a relatively small group of measurement types, namely motion, position, temperature, pressure, stress and force, and flow. Indicator type instruments, which provide visual readings of the quantity being measured, are generally useful in telemetry only in television and photographic applications. Their principles of operation, however, are used in many of the transducer type instruments; those instruments which provide an electrical signal containing the desired measurement information. It is this latter type which is of primary interest in P/A telemetry.

The function of a transducer is, by definition, to couple energy from one system into another system, or specifically, in telemetry, to employ measurement energy to (1) generate or control an electrical signal, (2) control the amount of current flow in a circuit, or (3) control the frequency or the phase of an electrical signal. In most cases the energy of measurement is mechanical, in the form of a displacement, and is used to actuate a moving part in the transducer. In some types of transducers, however, the measurement energy is not in this form. These types, which include the thermocouple, the thermistor, and the photoelectric, are used less widely than the mechanical, but have the highly desirable characteristic of placing only an infinitesimal load on the system under measurement.

The type of modulation to be used is a determining factor in the choice of the transducer action to be employed in obtaining the modulation signal. Both types (1) and (2) above are well adapted for pulse and amplitude modulation, and type (3) for frequency modulation. Some transducers are capable of producing two transducer actions, as is the resistance strain gage, which may be used as a variable resistance to control amount of current flow or in the frequency control network of a variable frequency oscillator. Although the strain gage transducer inherently best produces an amplitude modulating effect, the great versatility of the strain gage as a pickup for quantities desired in P/A telemetry warranted the additional work necessary to adapt it for frequency modulation in the form of the strain gage oscillator.

A second factor to be considered in transducer applications is the rate of variation of the measured quantity. Most transducers are electromechanical devices and as such have a resonant frequency determined by dimensions and other characteristics such as elasticity, density, mass, compliance, inductance, capacitance, and mechanical and electrical resistance. If this resonant frequency lies within the range of frequencies at which the measured quantity varies, an erroneous output will be obtained when variation occurs at this frequency.

The effects of resonance are minified by damping. Either fluid damping, in which the moving element has its motion restricted in forcing a cushioning fluid through an orifice, or electromagnetic damping, in which motion is restricted by an opposing force due to motor action on a slug or short-circuited coil passing through a magnetic field, is generally used, and the degree of damping is usually .60 to .70 critical. Because of the change in the viscosity of the damping fluid with temperature changes, the pickup output may vary considerably with temperature. Therefore data from pickups employing fluid damping must be corrected for these variations if the instrument's ambient temperature varies beyond prescribed limits. Electromagnetic damping has the advantage of negligible change in degree of damping with temperature.

Some transducers, such as the thermocouple, the thermistor, and the resistance thermometer, do not have a resonant frequency. The frequency of variation of the measured quantity is still important, however, because these transducers have a response or lag time which limits the rate of variation that can be accurately followed.

3. Signal Generating and Signal Controlling Transducers

As the name implies, these transducers produce or control an electrical signal, usually sinusoidal, containing the measurement information. In most cases the information is in the form of amplitude variation of a fixed frequency signal. This signal, upon amplification, may be used as the modulation signal, or may be transformed into some intermediate form before modulation of the carrier occurs. For example, the variable amplitude sine wave may be rectified and filtered if a D.C. modulation signal is desired. The more widely used types of signal generating and signal controlling transducers are the differential transformer, the variable coupling transformer, the electromagnetic, and the thermocouple. * These types will be described below. A few applications have been made involving piezoelectric and magnetostriction transducers but have not enjoyed very wide use.

a. Differential Transformer

The differential transformer, a signal controlling type often used in the measurement of vibrational amplitudes, makes use of a transformer consisting of a single primary winding, two series connected opposingly wound secondary windings, and a core of magnetic material. All or part of the core is movable in such a manner that when displaced from its neutral position there results an increase in the flux through one secondary and a decrease in the flux through the other. With a constant A.C. voltage applied across the primary and with no displacement of the core, signals of equal amplitude but of opposite phase are induced in the secondary circuit. The complete cancellation of these signals results in no output signal. With displacement of the core, the amplitudes of the signals in the two secondary windings differ, and the resultant output signal is proportional to the amplitude of the core displacement.

This type of pickup is desirable because the only loading it places on the moving body under measurement is, except for a negligible amount of magnetic coercion, the mass of the movable core. There is no mechanical connection or

* These and many other types of pickups are described, and the commercially available ones listed, in Douglas [6].

friction between this moving part and the remainder of the transformer. Other desirable characteristics are the small size and the large output signal obtainable from very small displacements. The small size advantage is partly nullified by the necessity of shielding between adjacent pickups to prevent magnetic linking, hence interference, between channels.

In a series of differential transformers manufactured by The Schaevitz Engineering Company of Collingswood, New Jersey, the primary winding occupies the center portion of a micarta tube and a secondary winding each end. The movable core is a cylinder of magnetic material which moves axially inside the tube. The sensitivity and the range of displacement over which the output is linear are determined by the length and diameter of the core. This line was developed for direct measurement of linear displacement of linear velocity, or for use in conjunction with other instruments for measurement of acceleration, pressure, or any other quantity the measuring of which might produce a mechanical displacement. This latter use applies, of course, to all pickups in the mechanical displacement category.

Another method of construction was used by The General Electric Company in a pickup of this type developed principally for incorporation in other instruments for measurement of various types of pressure. As can be seen from Figure 2, the displacement of some measuring element, such as a bellows or a diaphragm, causes the vertical center leg to move the laminated magnetic core material closer to the magnetic path of one "E" and farther from that of the other,

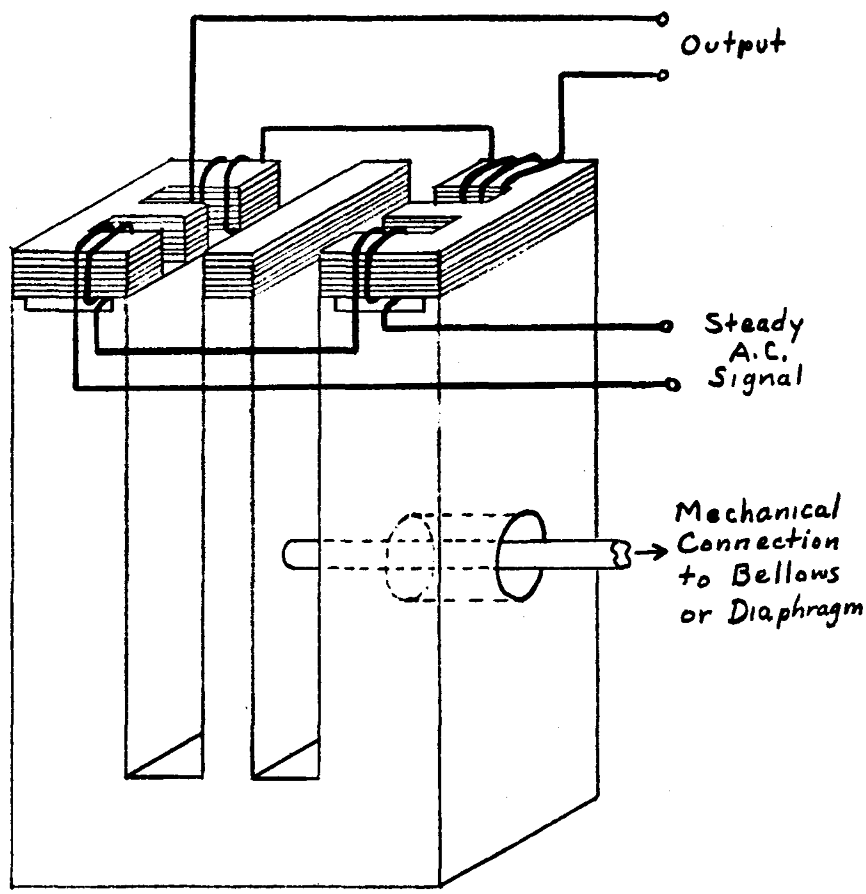


FIGURE 2. DIFFERENTIAL TRANSFORMER

From Fig. 4.222321, p.457,
"Pilotless Aircraft
Instrumentation Study"

so that an output signal results from the combination of the two unequal secondary signals. In this instrument, the output signal is rectified and filtered, delivering 0 to 5 volts D.C. when used with a 100,000 ohm load.

A third method of constructions, used by The Sperry Gyroscope Company, consists simply of an "E" shaped magnetic core with primary on center leg and differentially connected secondaries on the outer legs. The movable portion of the core is a bar across, but not touching, the open side of the "E". Motion of the bar, which is slightly shorter than the back of the "E", in a direction parallel to the back, results in an output signal because, as in the preceding types, of the inequality of the reluctance of the magnetic circuits of the two secondaries.

b. Variable Coupling Transformer

Less widely used than the differential transformer, but of simpler design, is the variable coupling transformer. This instrument, which consists of a fixed secondary winding and a rotatable core carrying a primary winding, provides an output which varies directly with the rotation of the core. An A.C. signal of constant magnitude is applied to the primary, and the voltage induced in the secondary, which is a maximum when the axes of the two windings are collinear and a minimum when they are normal to each other, is made to vary linearly with rotation angle by proper winding distribution and core design. Some of the smaller types of synchronous generators may be used as variable coupling transformers, with the difference that the output will vary as the cosine of the angle of rotation rather than linearly with rotation.

c. Electromagnetic

Of a similar general nature, but employing the principle of generation of an electromotive force in a solenoid by varying the magnetic flux linkages through the solenoid, is the electromagnetic type of pickup. In this type, the mechanical displacement of measurement is employed to produce relative motion between the two elements of the pickup. The pickup elements are coil and the magnet supplying the steady magnetic field. As in the conventional generator, the output voltage, when the relative motion is cyclic, is proportional to the velocity of the motion, or to the product of the frequency and amplitude of the motion, all values being instantaneous ones. For this reason, pickups of this type are often called "velocity" type pickups.

One instrument of this type, used in vibration measurements, makes use of a seismic mass suspended by springs inside a reference case which is secured to the body whose vibration is under measurement. One element of the pickup, either the mass or the case, comprises a permanent magnet whose magnetic field links a solenoid attached to the other element. When vibration occurs, the seismic mass remains stationary while the case moves with the vibrating body, so that the rate of change of flux linkages at any instant is proportional to the vibrational velocity at that instant, as is the resulting voltage generated in the solenoid. Since this output of the velocity pickup is proportional to vibra-velocity, it can be used directly as the modulating signal representing the instantaneous value of this quantity, or it may be fed to integrating or differentiating circuits to produce signals respectively proportional to the instantaneous value of vibrational amplitude or acceleration. Rectification of any of these signals produces a signal which represents the average value of the quantity involved. Unlike the two preceding transducer types, the velocity type is unable to generate a signal unless measurement motion is continuous.

Another method of obtaining this velocity type action is the employment of the mechanical displacement of measurement to vary the reluctance of two magnetic circuits with a common leg. Increasing the reluctance of one circuit while decreasing that of the other causes a change of flux through each and generates the desired electromotive force in a coil associated with each magnetic circuit. This signal, like that of the preceding pickup, is proportional to the vibrational velocity and may be used in like manner. In both cases, amplification is necessary to bring the signal to a level usable for modulation.

d. Thermocouple

Of the non-mechanical, signal generating transducers, the thermocouple is the outstanding type. It is the only instrument currently available which will measure high temperatures with any degree of accuracy under the severe mechanical and thermal conditions encountered in P/A power plants. Temperatures encountered at present are at the upper limit of the temperature range of thermocouples now available, and this presents a serious problem in that there is an expectation of much higher temperatures in power plants of the near future. At present, service up to 1600° C is available with platinum-platinum rhodium couples, but this material provides extremely low voltage output and requires protection against corrosion, contamination, and mechanical injury in the form of enclosure in a ceramic type protection tube. For temperatures up to 1300° C chromel-alumel is applicable and provides higher output than the platinum couple, while measurements below 1000° C may be made with the iron-constantan thermocouple, from which a still higher output is obtained. When iron-constantan is used above 600° C, however, protection tubes and a heavier gauge wire are generally necessary. Applications requiring extreme sensitivity necessitate small gauge wires, while high response rates are obtainable only with exposed thermocouple junctions. Although both of these conditions shorten thermocouple life, this type of operation may often be permissible in P/A applications because of the short operating life of the aircraft.

At best, the output voltage of a thermocouple is extremely low, consequently many difficulties are encountered in design of a satisfactory amplifier to bring the signal to a usable level with the required degree of accuracy and stability. Because of the relatively violent operating conditions, conventional pyrometer techniques involving sensitive galvanometers are not applicable. Strong advantages of the thermocouple are the small size and weight, ease of installation, and the negligible loading of the system being measured.

4. Current Controlling Transducers

The signal generating transducers described above employ many different principles of operation because there are many different methods of generating an electrical signal. The transducers whose action is to control current flow in a circuit employ, in general, variations of only one principle, that of varying a resistance to control the amount of current flow. The variations used in telemetry are the rheostat, the strain gage, the electron tube, the thermistor, and the resistance thermometer. These transducers employ the energy of measurement to control the value of a resistance. The last two of the types listed above differ from the others in that changes of temperature, rather than mechanical displacement, represent the energy of measurement. Any measuring device whose information can be expressed as a linear or angular displacement can be used in conjunction with a mechanically variable resistance transducer provided that frictional or inertia overloading does not occur. These transducers are used as current control devices in themselves and as bridge elements for voltage or frequency control.

a. Rheostat

The rheostat is generally used in the form of a potentiometer or a straight slide wire rheostat, with care being exercised in design and construction to achieve operation with very low driving torque. However, there are definite frictional and inertia loadings on the driving element, and in a given application these loadings must not be great enough to appreciably affect the performance of the measuring instrument. A high degree of linearity of output with quantity measured may be obtained by proper winding of the resistor. The microtorque potentiometer, developed by the G. M. Giannini Company of Pasadena, California, requires a driving torque of less than .003 ounce inches, frictional forces being reduced to a minimum by jeweled mounting of the resistor shaft and by the low contact pressures required because slip rings, brushes, and resistance wire are of platinum or platinum-iridium. Because of the small torque requirements, these potentiometers may be used in conjunction with many conventional measuring instruments without overloading the instrument. Coupling to the shaft of the instrument is made by direct mechanical connection or by magnetic coupling.

For P/A applications, because conventional instruments are usually more expensive and larger, specialized instruments have been developed, often employing principles of operation similar to those of the conventional instruments. Microtorque potentiometers are used in conjuntion with bellows for measuring gage of differential pressures, with seismic masses for use as accelerometers, and with various linkages for use in indicating vane, gyroscope, and other types of motions. Such characteristics as size, output, accuracy, resonant frequency, damping, and resolution depend upon the particular application and the ohmic value of the variable resistor. For example, with the type 2401 seismic mass linear accelerometer, also a Giannini product, accelerations ranging from minus 10 G to plus 10 G, or from minus 25 G to plus 25 G, may be measured with a resolution of 1/5 G, with the output resistance varying linearly with acceleration over any range from 0 to 100 ohms to 0 to 20,000 ohms, as desired. The natural frequency of the system is 8 cps and magnetic damping is employed. The unit is approximately 6 1/2 inches long, 1 inch in diameter, and weighs about 12 ounces.

b. Resistance Strain Gage

The resistance strain gage, which has long been useful in aircraft testing instrumentation, possesses many advantages not held by other pickups; it is versatile, being useful in measurement of a wide variety of variables; it is small, of the order of one inch or less in length; it has negligible inertia; in structural measurements of a body it can be attached directly to the surface, where stresses are usually a maximum and flaws most likely to occur; it can be applied to curved surfaces; it is inexpensive; it gives an output for negative as well as positive variations, i.e., for compression as well as tension; its change of resistance is linear with strain. In its most widely used form the strain gage consists of a length of small diameter wire cemented to a paper base. In use, the gage is cemented to the body under measurement and changes length with the body when strain occurs. The proportional change of resistance of the wire with length provides an indication of the amount of strain suffered by the body to which the gage is attached. Celluloid cement or some other waterproof, plastic cement is used for fastening the gage to the test structure. Because the adhesive force between the wire and the cement is proportional to the ratio of the wire's circumference to its cross sectional area, and because this force must be great, the diameter of the wire must be small; in practice, gage wire diameters range from .0005 to .0015 inch.

The ratio of resistance variation to strain, called the gage sensitivity factor, must be large in order to attain high measurement sensitivity. Although a gage factor of 12 is obtained with nickel wire and 5 with platinum-iridium, such factors as resistivity, thermal coefficient of resistance, and ease of gage fabrication led to general use of cupro-nickel alloys such as constantan, or nickel-chrome alloys such as nichrome, with gage factors of 2 to 3. In some cases a single length of wire may be used, but in most cases accuracy and sensitivity require a total length of wire many times the gage length, so that the gage is usually in the form of a flat grid, narrow in order to reduce transverse strain effects. A number of independent grids arranged in delta or rosette form may be used in resolving components of a strain whose exact direction is unknown. The principal sources of error in the strain gage are the change of resistance with temperature and the thermo-electric effect at the junctions of gage terminal strips and lead-in wires. The latter effect is negligible with nichrome terminals and copper wire, and in other cases is reduced by maintaining both gage joints at the same temperature, covering junctions with insulating sleeves and tape, and using solid, rather than stranded, lead-in wire to avoid differences in the number of conductors. Temperature effects are lowered by use of gages in bridge circuits in such a manner that changes due to temperature are equal and opposite in two gages and thus balance out, the gages being close enough together that their temperatures are practically the same.

Like the thermocouple, the strain gage suffers the disadvantage of extremely low output. In conventional ground applications of strain gages, galvanometers and other sensitive amplifiers are available, but in P/A applications severe operating conditions prohibit the use of these sensitive units. A certain amount of gain may be achieved by use of bridge circuits. For example, in the Wheatstone bridge shown in Figure 3, assume the use of a strain gage for R_a and fixed resistors for R_b, R_c, and R_d, with a constant input voltage E_i, gives a certain output voltage E_o.

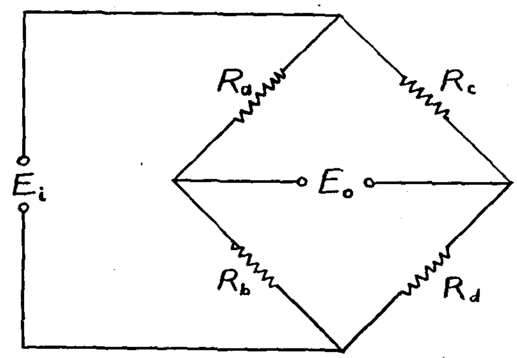


Figure 3. Strain Gage Bridge

If strain gages are used for R_a and R_b, so connected as to have oppositely changing resistance when strain occurs, the output voltage will be 2 E_o. Finally, if all four resistors are strain gages, with R_a and R_d increasing while R_b and R_c decrease with strain, the output will be 4 E_o.

This increase in output is accompanied by increased difficulty of balancing, and in the last case this difficulty might prohibit the use of the circuit where considerable vibration is expected.

The use of the strain gage as a frequency controlling device, which will be discussed under the section on frequency controlling transducers, is virtually a method of amplifying the small change of resistance of the gage, but the output signal is in the form of a varying frequency rather than a varying voltage.

The strain gage is particularly useful in aircraft structural measurements, for which use they were originally conceived. They may be used for measurement of strain and vibration in almost any part of the aircraft. In other applications the strain gage is bonded to the surface of a metal diaphragm and the strain on the pressure-actuated diaphragm results in a change of strain gage resistance which is proportional to the applied pressure. Also, the thrust of an engine may be measured by bonding strain gages to a beam which is deflected by the thrust.

Another instrument which is well adapted for use with the strain gage is the loaded cantilever beam accelerometer. If it is desired to measure a vertical acceleration, either positive or negative, one end of a horizontal cantilever beam is secured to the body under test. The free end is mass loaded. Near the clamped end of the beam, where strain is greatest, a strain gage is bonded to the top side of the beam, and another to the lower side. These gages, when the beam is deflected, change resistance in opposite manner, one being under tension and the other under compression, and are thus suited to the type of bridge circuit described above. The strain in the beam, hence the change in strain gage resistances, are proportional to the acceleration deflecting the mass, and a linear change of output signal with acceleration is obtained.

Besides the conventional method of fastening or bonding the strain gage to a body under strain, the gage may be used as a restraining element of a vibrating structural member, diaphragm, or mass. This principle is employed in a line of instruments manufactured by The Statham Laboratories, Los Angeles, California, capable of measuring force, pressure, acceleration, and small displacements.

c. Electron Tube

Because it is inherently a current controlling device and because its operating characteristics are affected by the physical location of its electrodes, the electron tube has been adapted for use as a transducer which transforms the mechanical displacement of measurement into a variation of electrical current. A variation of any of the inter-electrode distances in a tube will result in a change in the tube's plate current. Tubes have been developed in which the control grid is the movable element, while in others the plate is moved by the mechanical measurement force.

Many difficulties were encountered in the development of movable element tubes. The problem of entering the tube envelope was solved by use of a shaft passing through a diaphragm, the diaphragm being made of Kovar and sealed to the glass envelope. The stiffness of the diaphragm must be so low as to offer negligible mechanical impedance to the measurement system. Also, the resonant frequency of the movable electrode must be outside the measurement frequency range. The mass of the moving element must be low so as to avoid inertia effects. If motion of the element is in any direction other than the direction of measurement motion, spurious current changes may occur. This possible source of distortion is eliminated mainly by diaphragm design.

A tube developed at the <u>Naval Research Laboratory</u> is in the form of a twin triode with a common plate. Motion of the plate results in decreased distance to one cathode, and increased distance to the other. The two sections of the tube form two legs of a simple bridge circuit. Excellent linearity was attained in this tube. Sylvania Electric Products has produced an electron tube accelerometer. It consists of two movable plates with a cathode between them, and acceleration of the tube in a direction along the line in which the elements are mounted causes one plate to move toward the cathode and the other to move away from it. The two changing resistances represented by the two diodes are used as adjacent arms of a bridge circuit.

The electron tube transducer was developed primarily for use as a phonograph pickup, and to date has been little used in telemetry. They give promise of many applications when further development and greater ease of manufacture are accomplished.

d. Thermistor

The thermistor is a device whose electrical resistance varies widely with temperature, the active element of the device being composed of a solid semiconducting material. It has been known for many years that semiconductors were characterized by large negative temperature coefficients of resistance. Although this characteristic gave promise of many useful applications and thus resulted in considerable effort toward development, difficulties due to the tremendous effects of impurities, heat treatment, methods of making contacts, and treatment during use retarded advancement until research and study of the nature of semiconductors recently made it possible to produce thermistors of the required accuracy and dependability.

Fabrication and quality control are still critical but thermistors are now being produced in many forms. The semiconductors used are mixtures of metallic oxides; one material consists of oxides of manganese and nickel, another the oxides of manganese, nickel, and cobalt. According to Becker [1], the first material mentioned has, at 25° C, a temperature coefficient of resistance of -4.4 percent per centigrade degree, which is over 11 times that of copper, which is .39 at the same temperature. Because of this property, thermistors composed of such materials are well adapted for use as sensitive temperature measuring devices. Furthermore, they are simple, small, rugged, have long life, and require little maintenance.

The thermistor may be used in bridge circuits of the type employed with the strain gage, but it is important that the measuring current be held low enough that it results in no appreciable heating of the thermistor, thus insuring that all resistance changes are produced only by ambient temperature variations. The high resistance values for which thermistors can be designed make the resistance, hence the resistance changes, of the lead wires negligible. This makes possible the placing of the thermistor at a point distant from its amplifier. Measurements of changes of the order of .0005 centigrade degree can be made using a thermistor in conjunction with a sensitive galvanometer, but the use of a galvanometer of the type required is not feasible in pilotless aircraft. Also, this degree of sensitivity is not required.

The time constant of a thermistor is defined as the time required for the temperature of the thermistor to change 63 percent of the difference between its initial value and that of the surroundings. In applications involving rapidly changing temperatures, thus requiring low thermistor time constant, the thermistor may take the form of a very small bead or may consist of flakes of the semiconductor material deposited on a ceramic base, With small beads time constants below one second may be obtained; with flake form, as low as one millisecond. For nonspecialized applications, thermistors may be made as a rod, a bead, or a disc; they are also manufactured in the form of a probe which can be projected into a fluid stream.

The thermistor's principal disadvantage, and a very serious one, is its limited temperature range. If temperatures of 300° C are exceeded, the stability, hence accuracy, and the life of the thermistor are impaired. This characteristic limits their applications at present to those measurements in the range from -25° C to 375° C, which are mostly of ambient temperatures. Higher temperatures can be measured indirectly by focusing heat radiation on a thermistor by means of a suitable mirror. The heat energy is greatly reduced, however, so that more sensitive amplifiers are required. Also, any vibration causing change of position of the hot body, the mirror, or the thermistor would result in a difference of radiation reaching the thermistor. Since this difference was not caused by a change in temperature of the hot body, it represents erroneous information.

e. Resistance Thermometer

As in the case of the thermistor, the change of electrical resistance with temperature is the principle of operation of the resistance thermometer. In its most common form, the device consists of a metallic filament whose resistance varies with the temperature of the surroundings. The temperature coefficient of resistance is much lower for metals than for semiconductors, and is positive for most metals. The reduced sensitivity is partly compensated for by the much greater range, temperatures up to about 1000° C being allowable for platinum wire. For temperatures up to 400° C, nickel-iron alloys and pure nickel may be used. The thermometer is often used as part of a simple voltage divider across a battery, the voltage across the thermometer being proportional to the temperature being measured.

When this or any other thermometry method is used to measure the temperature of the air surrounding the aircraft, the device is usually enclosed in a protecting shield. The changes in temperature resulting from varying air pressures, due to the motion of the missile through the air, require corrections which are proportional to the airspeed. This correction may be applied to the data upon analysis, but in some cases the shape of the housing is so designed as to effect the correction.

The measurement of absolute pressure by use of the resistance thermometer is accomplished in the Pirani gage. In this gage, the temperature of the resistance thermometer is determined by the heat conductivity of the residual gases, which is itself dependent upon the absolute pressure. The thermometer may be used as part of a voltage divider across a battery, or as an element of an initially balanced bridge. The voltage across the thermometer element, in the first case, or the degree of unbalance of the bridge, in the second, may be calibrated directly in terms of pressure.

5. Frequency Controlling Transducers

For a measured quantity to control the frequency of an electrical signal, it is necessary for the associated transducer to produce a variation in some element of the frequency controlling network of the signal-generating oscillator. The most direct method of accomplishing this is to use the energy of measurement to vary the inductance or capacity in the oscillator tank circuit. At audio frequencies, the large size of capacitor which would be required makes preferable the use of a variable inductance. An indirect method of producing this frequency variation exists in the form of the strain gage oscillator, which was developed to permit the use of the strain gage in a frequency modulated subcarrier system. Another method of obtaining frequency control, or frequency modulation, of a subcarrier is by use of a D.C. signal, which is proportional to the quantity measured, to control the frequency of a positive grid return multivibrator.

a. Resistance Strain Gage

In order to use the strain gage as a frequency controlling transducer, the Princeton telemetering group developed the strain gage oscillator, later called the "strage." The oscillator comprises a two stage resistance coupled amplifier with output coupled to input through a phase shifting network. Oscillation occurs at the frequency for which the phase shift through the circuit is zero. Because the sensitivity of the system is determined by the change of frequency with strain gage resistance, it was desirable to develop a phase shifter having a great change of phase with gage resistance, used with an amplifier having little change of phase with frequency, so that a small change in gage resistance would result in a considerable change in frequency.

In Figure 4 (a), a simplified schematic of the strage, R_a and R_b are strain gages; R_c and R_d, calibrating resistances.

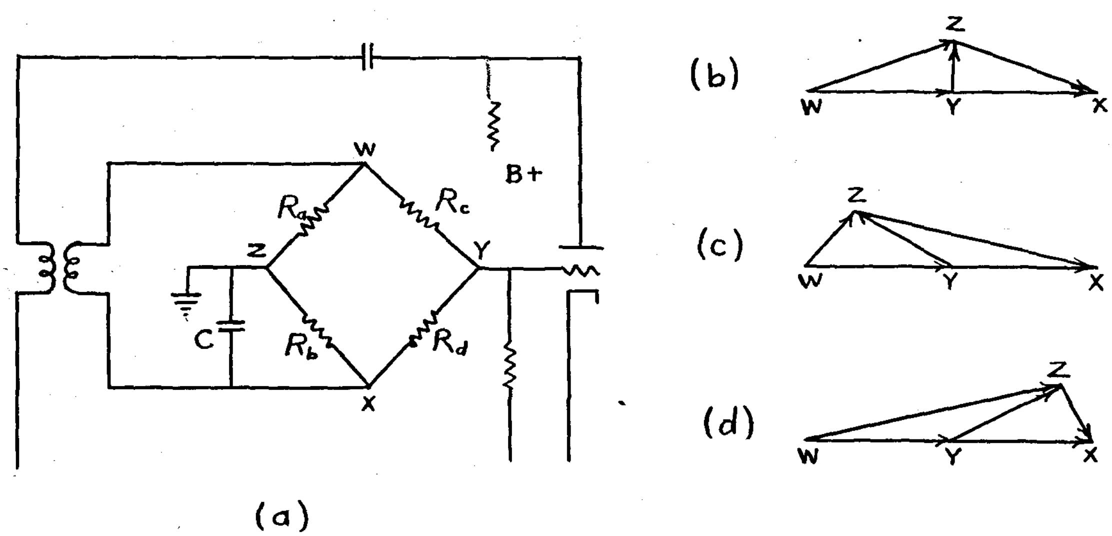


Figure 4. Strain Gage Oscillator

The presence of small capacity C makes balance of the bridge impossible, hence always assures an output voltage E_{yz}. The strain gages are so bonded to the strained member that when strain occurs, the resistances of the gages vary oppositely, thus giving a greater unbalance of the bridge than would be obtained using one gage and a fixed resistor for R_a and R_b. Figure 4 (b) shows qualitatively the voltage relationships in the bridge circuit with R_a and R_b approximately equal; (c) for R_a much less than R_b; and (d) for R_a much greater than R_b.

It is seen that the phase of the signal applied to the grid of the amplifier, E_{yz}, varies widely with the strain gage resistance. Thus a large change of oscillator frequency is necessary in order to make the total phase shift around the ring be zero. Percentage changes in frequency of the order of 50 times the percentage changes in gage resistance were achieved by the Princeton group. In practice, there is required more amplification than is indicated in the simplified schematic shown. It should be noted that the use of the strage principle need not be limited to strain gages as the variable resistance.

b. Variable Inductance

In the Bumblebee telemetering system, developed by Palmer Physical Laboratory, Princeton University, the frequency of the subcarrier oscillator is controlled by a variable inductance which tunes the tank circuit. The inductance consists of a coil mounted on the center leg of a laminated "E" core. The magnetic path of the core is completed through air gaps to a movable bar across the legs of the "E". Motion of the bar in accordance with variations in the measured quantity results in a changing air gap, and thus the inductance of the coil is changed by the change in its core reluctance. The bar is carried by a diaphragm whose design is determined by the intended use of the transducer. For example, for pressure measurements a corrugated beryllium-copper diaphragm is used, and for acceleration measurements a smaller, mass loaded diaphragm is used. The inductance coil is tapped for use in a conventional Hartley oscillator.

c. Positive Grid Return Multivibrator

In looking for a simple, stable, linear subcarrier frequency modulator, the Princeton telemetering group developed the circuit shown in Figure 5 (a). The oscillator section, consisting of tube V2, V_3, and their associated components, is simply a positive grid return, free running multivibrator. Frequency determining factors in a multivibrator of this type are the electrode potentials, the tube characteristics, and the time constants of charge and discharge of condensers C_1 and C_2. Frequency modulation of the oscillator is accomplished by variation of the D.C. potential to which the control grids of V2 and V3 are returned, this being the plate potential of tube V1. Application of a D. C. voltage, proportional to the measured value of the variable being telemetered, to the control grid of V1 causes variation of plate current, and therefore of plate potential, of this tube.

In the Princeton telemetering system a linear change of frequency with modulator grid voltage was obtained, a plus or minus 7.5 percent frequency deviation being obtained with a change in grid voltage from 0 to 4 volts D.C. The circuit is sensitive to filament voltage variations, however, and compensation is obtained by connecting the modulator tube cathode to a voltage divider between filament supply and ground. The high output voltage swings which are characteristic of the multivibrator permit the use of light weight RC filters in spite of their high attenuation factors. Filtering of the oscillator output is necessary because the output is very nearly a square wave and a sinusoidal form is desired. Frequency variations caused by plate supply voltage changes are reduced by use of a regulated supply. In Figure 5 (b) and (c) are shown the variation of oscillator frequency with grid, plate, and heater potentials.

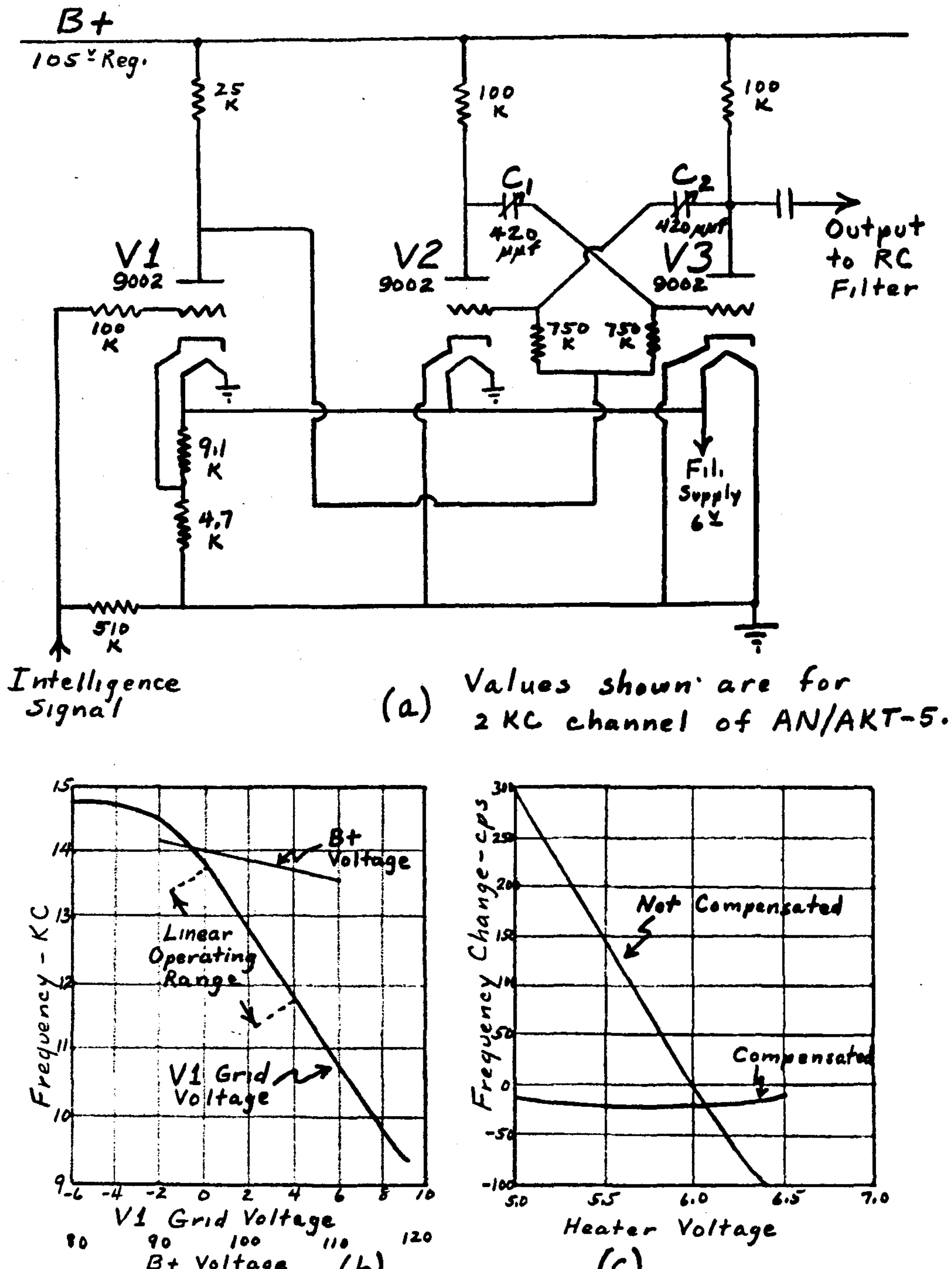


Figure 5. Positive Grid Return Multivibrator Modulator

III. MULTIPLEXING, MODULATION, AND TRANSMISSION

The characteristics of a system as regards multiplexing, modulation, both of the subcarrier and the radio frequency carrier, and transmission are so closely interdependent that they will be considered together, being separated only as to type of modulation; amplitude, frequency, or pulse.

As was previously pointed out, all telemetering systems in present use employ either frequency sharing (subcarrier) or time sharing (commutation) multiplex. The subcarrier multiplex makes use of a number of audio frequency oscillators to generate subcarriers, each of which contains the intelligence of a given channel in the form of amplitude or frequency modulation, pulse modulation being possible but seldom used. These modulated subcarriers are then synthesized into a complex signal which modulates the radio frequency carrier. After demodulation in the receiver, the synthesized signal is separated into its original components by a system of band pass filters, there being one filter for each channel. The demodulation of each subcarrier then provides the original modulating intelligence.

The commutation multiplex employs some form of switching channels in regular succession so that the output of each transducer, direct or amplified, modulates the radio frequency carrier for a definite portion of the commutation cycle. After reception and demodulation, a commutator, synchronized with that in the aircraft, separates the complex signal again into the individual channel signals. Further demodulation is not necessary, as it was in the subcarrier system, because each channel, during its portion of the commutation cycle, modulated the radio frequency carrier directly.

1. Amplitude Modulated Subcarrier Multiplex

In the amplitude modulated subcarrier system, the modulation signal may have frequency components from slightly less than the subcarrier frequency f_c to zero.* As the modulation frequency f_m approaches f_c the side band frequencies approach zero and $2f_c$, and in detection the carrier may be separated from the lower side band by means of an ideal low pass filter with cut-off frequency equal to f_c.

Practical considerations render these theoretical limits impossible to achieve. Information which varies nonsinusoidally results in modulation signals having a large number of component frequencies, abrupt variations involving very high frequency components. For this reason, it is the highest expected modulating frequency which is represented by f_m above, and this frequency is usually considerably above the fundamental frequency of the variation. Another factor which requires even greater separation of the modulation and subcarrier frequency is the filter which removes the subcarrier

*For a more complete treatment of the multiplex considerations given here, see Rauch [22] , [23] .

frequency in the demodulation process. These factors result in the practical requirement that the subcarrier frequency be 10 to 15 times the frequency of variation of the measured quantity. Thus, in a system intended to accommodate measurements varying up to 100 cps, the frequency of the lowest channel subcarrier would be of the order of 1500 cps.

The preceding paragraph indicates the manner in which the lowest subcarrier frequency is determined. Also important is the determination of the other channel frequencies. In his analysis of amplitude modulated subcarrier systems, Stedman [25] shows that no significant decrease of distortion due to nonlinear transmission is accomplished by so selecting filter midband frequencies that harmonics of lower subcarriers fall outside the pass bands of the higher frequency channel filters.

Consider a subcarrier system of n channels with a transmission system response characteristic represent by

$$e_o = A_1 e_i + A_2 e_i^2 + A_3 e_i^3 , \tag{1}$$

where the coefficients A_1, A_2, and $A_3$are independent of frequency, and the input signal is of the form

$$e_i = \sum_{\alpha=1}^{n} E_\alpha \cos \omega_\alpha t. \tag{2}$$

The third order cross modulation products resulting from the nonlinearity of the transmission system include third harmonic, fundamental, and sum and difference, or cross product, terms. The second order terms are negligible in comparison with the third order terms if n is large and A_2 not very much greater than A_3.

The third order cross products are of the form

$$3\left(\frac{A_3}{4}\right) E_q^2 E_p \cos\left(2\omega_q \pm \omega_p\right)t \qquad (3)$$

and

$$6\left(\frac{A_3}{4}\right) E_p E_q E_r \cos\left(\omega_p \pm \omega_q \pm \omega_r\right) t, \qquad (4)$$

with p, q, and r representing specific values of α. There is a large number of these terms; 2n(n-1) of the former and $\frac{4}{6}$n(n-1)(n-2) of the latter, or 364 and 1456, respectively, in the 14 channel Boeing system discussed by Stedman. He states that in this system, by actual count, there are about 50 of these cross product signals which, in passing through a given channel filter, are attenuated less than 3 db.

Because the amplitude of the third harmonic signal is of the order of the amplitudes of the cross product signals, and because only one third harmonic signal may exists in a given channel while about 50 cross products exist, it is seen that the harmonic constitutes only a very small percentage of the spurious combination tones resulting from nonlinear transmission. Thus little is gained by the spacing of subcarrier frequencies to prevent harmonics of lower channels falling within the pass bands of the upper channel filters. The cross product signals are too evenly and too widely distributed in frequency to avoid, so the only effective method of reducing this distortion is to reduce A_2 and A_3, i.e., increase the linearity of the system.

In a system in which the number of channels is small, it is possible to so assign each channel's pass band as to avoid the harmonic and cross product terms of the lower channels. But when the number of channels exceeds 4 or 5, excessive spectrum is required to provide the required number of the clear zones.

The spurious tones of forms (3) and (4) are so numerous and so evenly distributed that they form a fairly continuous spectrum of cross modulation noise. There is, however, an even more important third order cross modulation product of the form

$$6\left(\frac{A_3}{4}\right) E_q^2 E_p \cos \omega_p t. \tag{5}$$

It is seen that this represents a variation in the level of the desired signal caused by interference from signals in other channels. In the case given here, for example, the desired output signal, undistorted, may be represented as

$$A_1 E_p \cos \omega_p t. \tag{6}$$

The presence of term (5), caused by cross talk from the q^{th} channel, thus changes the amplitude of the coefficient of the desired signal from A_1E_p to $\left[A_1 + 6\left(\frac{A_3}{4}\right)E_q^2\right]E_p$.

Stedman [25] shows that the r.m.s. value of the cross modulation noise is considerably lower than the change in signal level just described, and for this reason suggests the use of the latter effect as the principal overload criterion. That is, establish the permissible signal levels in the various channels for a given percent distorition due to terms of type (5), assuming equal signal levels in all channels.

2. Frequency Modulated Subcarrier Multiplex

The principal advantage of using a frequency modulated subcarrier multiplex is the suppression of interference due to cross modulation between channels. Defining K as interference modulation, Hund [14] gives the value of K in A.M. and F.M. receivers as

$$K_{A.M.} = \frac{I}{D} \tag{7}$$

$$K_{F.M.} = \frac{I}{D} \frac{F_1 - F_2}{\Delta F} \tag{8}$$

where

- I = amplitude of interference signal
- D = amplitude of desired signal
- F_1 = frequency of interference signal
- F_2 = frequency of desired signal
- ΔF = frequency deviation, or one half the F.M. bandwidth

It is seen that, in the case of A.M., K is independent of the signal frequencies. For a system of equivalent non-linear distortion, $K_{F.M.}$ is less than $K_{A.M.}$ if the frequency difference between the interfering and desired signals is less than half the F.M. bandwidth. Although $K_{F.M.}$ is greater than $K_{A.M.}$ for (F_1-F_2) greater than ΔF, these higher values of frequency represented by (F_1-F_2) may be above the high frequency response of the recording equipment. As shown in Palmer [18], if the upper frequency limit of the recorder is R, then for (F_1-F_2) greater than R,

$$K_{F.M.} = \frac{I}{D} \frac{R}{\Delta F} . \tag{9}$$

For example, in the Princeton telemetering system, one channel has a ΔF of 405 cps. When used with a recording galvanometer whose upper frequency response limit is 100 cps, it is seen that the maximum possible interference modulation with F.M. is

$$K_{F.M.} = \frac{100}{405} \frac{I}{D}, \qquad (10)$$

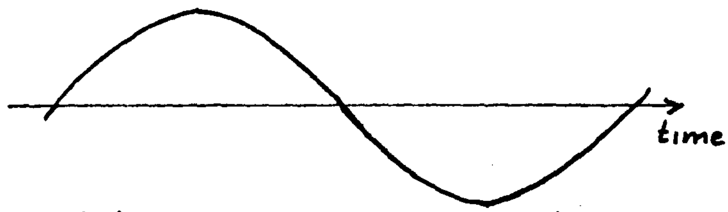
which is less than one fourth the interference modulation for A.M.

The simplicity and stability of the methods previously described for frequency modulating a subcarrier also recommend the use of this type multiplex.

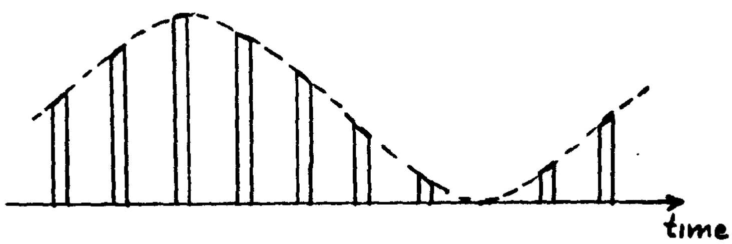
3. Commutation Multiplex

In any commutation multiplex system, the intelligence of a given channel may be represented by a series of pulses of variable amplitude, recurring at the sampling frequency f_s. The Fourier expansion of a signal of this form indicates frequency components, of various amplitudes, at frequencies f_m, f_s, and all integral multiples of f_s. As the channel intelligence varies, these frequency components vary in amplitude but remain fixed in frequency, and so have associated with them the normal amplitude modulation side bands. These representations are shown in Figure 6, and it must be noted that only a single channel is involved.

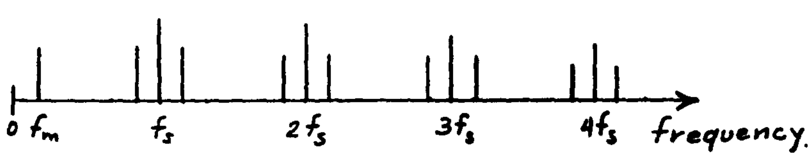
To avoid overlapping of adjacent sidebands and the resultant distortion, it is necessary that f_m be less than the available side band spectrum, which is $f_s/2$. Theoretically, this means that a sinusoidal variation can be reproduced if the number of samples is anything greater than 2 per cycle. As 2 is approached, however, an ideal filter is required to reject the next adjacent sideband, and at the value 2 there



(a) Modulation Signal



(b) Amplitude Modulated Pulses



(c) Fourier Components of (b) with associated amplitude modulation side bands.

FIGURE 6. REPRESENTATION OF INTELLIGENCE IN ONE CHANNEL OF A COMMUTATION MULTIPLEX

exists an ambiguity which allows an infinite number of signals of proper frequency but differing amplitudes.

For practical purposes approximately 7 samples per cycle are necessary for reliable reproduction of a sinusoidal variation, so that a sampling rate of 7 times the frequency of variation is required for quantities changing in this manner. It follows that a variation of more complex form requires a higher sampling rate, and that slow, more or less linear variations, such as are encountered in temperature and pressure measurements, may be sampled at a much lower rate.

Where exceedingly great differences in variation rates occur, most subcarrier systems commutate one or two channels to obtain measurements of many slowly varying quantities, and employ the remaining channels to telemeter more rapidly varying quantities. For example, in a four channel subcarrier system, one of the channels might be commutated among 30 subchannels by a rotary switch being driven 480 rpm. Each subchannel is thus sampled 8 times per second so that a sinusoidal variation of about one cycle per second may be satisfactorily measured by each subchannel. If a quantity to be measured varies at a low rate, but at a rate which cannot be accommodated by any single subchannel, a number m of subchannels may be paralleled to the transducer in question and thus accept a variation rate which is m times the rate tolerated by one subchannel.

In the preceding example, the frequency response of the uncommutated channels is dependent upon the type of subcarrier modulation employed, as was previously discussed.

In a time sharing multiplex system, commutation may be achieved either mechanically or electronically. In mechanical commutation, motor driven commutators, similar to rotary switches, are used, with particular care being used in choice of contact metal, contact pressure, and electrode spacing. Silver contacts wear very quickly at the high speeds used, but reduced wear was achieved by peening a small steel ball into the end of the contact arm, thus obtaining a rolling contact. Although comparatively high mechanical speeds are used, mechanical commutation does not provide nearly as high switching rates as are available with electronic commutation.

Several forms of electronic commutators have been developed. A multiple anode cathode ray tube called the "cyclophon" was developed by Federal Telecommunication Laboratories, Inc. In this tube a circularly swept electron beam scans a metal plate containing a number of apertures arranged in a circle. Behind each aperture is an electrode called the dynode. Each dynode represents a channel, and secondary emission occurs when a dynode is hit by the electron beam; a signal is thus produced across a resistance in the dynode circuit. Using secondary emission increases the operating current and isolates the output circuit from the primary electron beam. One type of cyclophon is capable of multiplexing 25 channels at the rate of 8,000 cps. Other beam switching tubes have been developed and some are under development.

Also in use in electronic commutation are various types of chains of switching circuits, in which a master trigger pulse initiates a sampling sequence. The triggering of each succeeding channel may be accomplished when the preceding channel is cut off, or a separate trigger pulse may switch in each channel. The length of time a channel remains switched in is determined by the intelligence on that channel.

A third electronic commutation method is the use of lumped constant delay lines. A trigger pulse is passed through a delay line, the delay of one section of the line representing one channel width, As the pulse arrives at the end of a given section of the line, the corresponding channel is triggered.

The higher speeds attainable in electronic commutation, with the resultant increase of channel frequency response, gives this type considerable advantage over the mechanical type. This high speed of commutation is one reason for the great information carrying ability of pulse systems. However, there must be a compromise between the number of channels, the channel frequency response, and the blank interval between channels. As was pointed out before, this blank interval must be slightly greater than the recovery time of the transmission link in order to prevent adjacent channel cross talk.

4. Radio Frequency Transmission Link

In considering the type of radio frequency link to be used in a telemetering system, it is necessary to compare a number of characteristics of amplitude modulation (AM), frequency modulation (FM), and pulse modulation (PM). Included in pulse modulation discussion will be the types more applicable to telemetering; pulse time modulation (P.T.M.), pulse interval modulation (P.I.M.), pulse amplitude modulation (P.A.M.), and pulse width modulation (P.W.M.). The requirements of the specific application as to information handling ability, accuracy, transmission range, size, and weight require a consideration of bandwidth, signal-to-noise ratio, distortion, frequency, and power.

The bandwidth required in using an A.M. transmission link is less than for F.M. or P.M., but the signal-to-noise ratio is also considerably less. This last is a serious disadvantage, and, because at present the necessity for conserving bandwidth does not exist, very few systems employ A.M. radio links. Because the noise input of a receiver increases as the receiver bandwidth increases, the advantage in signal-to-noise ratio appears to be with F.M. rather than P.M. in that the former requires less bandwidth. However, while the ratio of bandwidths required might be of the order of 2 or 3, in a pulse system such as that of the Naval Research Laboratory a duty factor of .005 permits an increase of pulse power of 200 times the power in an equivalent F.M. system. * Therefore, a gain in signal-to-noise ratio of the order of 100 is realized in using P.M.

A difficulty encountered in A.M. and P.A.M. links is the fact that non-linear distortion may be introduced not only in

* Hoeppner [12] .

the modulator and demodulator, but in all intervening radio frequency stages. This difficulty does not exist in systems in which limiting is employed, as in F.M., P.T.M., P.W.M., and any other pulse modulation system in which the amplitude of the pulses undergo limiting. It must be remembered, however, that this advantage does not exist unless limiting occurs, hence may be lost with very weak signals.

The introduction of cross talk between channels by non-linearity of the transmission system was described in the discussion of the A.M. subcarrier multiplex. Although, as stated in the preceding paragraph, non-linear distortion may occur in any given channel of a P.A.M. system, the interchannel cross talk of the system is not determined by the non-linearity of the transmission link. It was shown in the discussion of the commutation multiplex that a P.A.M. signal is made up of A.M. carriers at the pulse repetition frequency f_s and its harmonics. The components of a given channel are separated in time from the components of the adjacent channels so that cross talk effects due to non-linear transmission are impossible.

Instead, the transient response of the transmission system determines whether cross talk between channels will exist. If the transient response is poor, a component of one channel may be prolonged into the time interval which should be occupied only by the corresponding component of the following channel and thus affect the amplitude of the latter component. In other words, to avoid cross talk it is necessary that the transmission link be able to return to its "neutral" condition in the interval between switching out one channel and switching in the next. This indicates the necessity of a finite blank interval between channels and this interval is provided in the design of the commutator.

In general, the output frequency of an amplifier is the same as the input frequency, although the phase is shifted. This indicates therefore, that there is little possibility of non-linear, or amplitude, distortion in the intermediate frequency and radio frequency stages of an F.M. system. For this reason, the total non-linear distortion is generally assumed to be in the modulator and demodulator stages. Rauch [23] points out, however, that if the deviation ratio is too small, non-linear distortion may be introduced in the following manner.

Let Figure 7 represent the total pass band and phase delay characteristics of all the stages between the modulator and the demodulator stages. The modulation signal amplitude variations cause the instantaneous frequencies of the various components to move about in the pass band. It is seen that an increase in frequency is accompanied by an increase in phase delay. Increasing phase delay results in an incremental decrease in frequency. This change in frequency is equivalent to a change in the amplitude of the modulation signal, but distortion does not result if the phase delay characteristic is linear. In that case, the only result is a phase shift of the modulation signal. When the characteristic is non-linear, as it usually is near the limits of the pass band, distortion

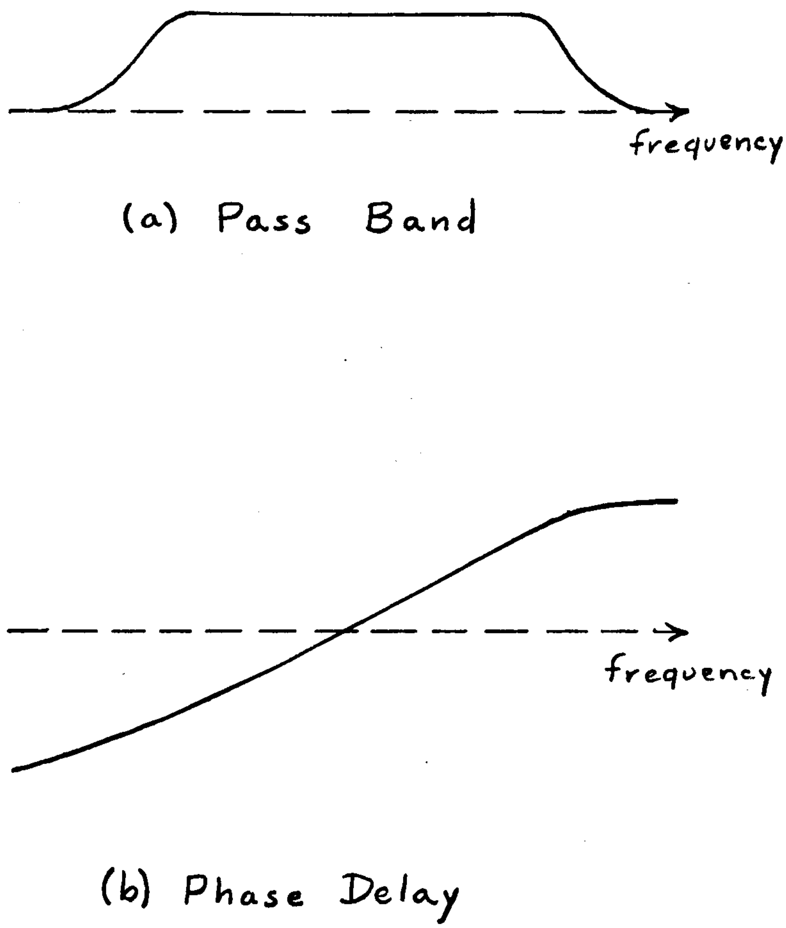


FIGURE 7. HYPOTHETICAL PASS BAND and PHASE DELAY CHARACTERISTICS of an F.M. TRANSMISSION LINK.

From L.L. Rauch; "The General Problem of Multiplexing," Bumblebee Report No. 42.

occurs because a component traversing the pass band at a given rate undergoes different phase shift, hence different incremental frequency change, at the various positions along the pass band. The distortion introduced varies directly with the rate of change of phase delay with time, which in turn varies with the frequency of the modulation signal.

Distortion of this type may be eliminated by use of a deviation ratio, or modulation index, large enough to insure that the significant components of the frequency modulated radio frequency signal fall well within the linear portion of the phase delay characteristic. Early F.M. systems used in telemetering, employing deviation ratios of 2 or less, suffered this type of distortion. Use of deviation ratios of the order of 5 or above make valid the assumption that no non-linear distortion is introduced in the F.M. radio frequency link.

The choice of a frequency for the transmission link involves several considerations. A very high frequency is indicated in antenna requirements. The antenna must not affect the aerodynamic characteristics of the aircraft; antennas for frequencies in the hundreds of megacycles are small and are flexible in configuration. To prevent reception of reflected signals, the ground system antenna must have good directivity, again indicating high frequencies to keep the size of the antenna small. Another factor affecting the minimum satisfactory frequency is the effect of the ionosphere on the signal; at lower frequencies, phase shift, refraction, and variation in arrival time may result from this cause.

Factors affecting the upper frequency limit are atmospheric absorption, shadowing of the excessively small transmitting antenna by the body of the aircraft, and ground antenna directivity. If directivity is too great, the signal is easily lost. Also, the small size of the antenna results in a decrease of received energy. From these and other considerations, Hoeppner [12] suggests a lower limit of 100 to 200 megacycles, and an upper limit of 2000 megacycles, for maneuvering or fast moving missiles, to 3000 megacycles, for long range, high altitude missiles. Because shadowing effects are bad above the resonant frequency of the aircraft body, several antennas are required if the frequency used is higher than missile resonance.

The high frequencies indicated above for use in telemetry make the great band width requirements of pulse modulation only a minor disadvantage. Other considerations of the various types of pulse modulation will be discussed with the aid of Figure 8. Four types of pulse modulation multiplex are illustrated. (a), (b), and (c) represent the modulation signals in channels (1), (2), and (3), respectively, of a three channel system.

In the same figure, (d) shows the multiplexing of these channels using P.A.M., in which the pulse interval and pulse width remain constant while the pulse amplitude is proportional to the instantaneous value, at time of sampling. of the modulating signal being sampled. As was mentioned before, P.A.M. inherently has lower signal-to-noise ratio than other types of P.M. and is subject to non-linear distortion in the transmission link, hence is not used in telemetering.

(e) represents P.I.M. multiplex. In this case the amplitude and width of the pulse are constant and the intelligence is contained in the interval between successive pulses. This type, like the other constant amplitude types, has the previously described advantages which result from limiting action. P.I.M. was employed in the original Naval Research Laboratory equipment, but several disadvantages were noted. Calibration was difficult and a visual check of channel operation by oscilloscopic examination was rendered difficult because modulation of one channel caused movement of the pulses of all following channels. This sequential occurence of pulses is obtained by use of a chain of one-shot multivibrators, one for each channel. Each is triggered by the preceding stage, produces a square pulse whose time period is proportional to the instantaneous value of the corresponding intelligence signal, and triggers the following stage when the pulse ends.

(f) shows P.W.M. of the three channels. The intelligence signal is represented in the width of the pulses; the pulse amplitude and interval remain uniform. Either the leading or trailing edge of the pulse may remain fixed, and the other edge modulated between certain limits. For example, the unmodulated pulse width might be 3 microseconds, with maximum positive and negative modulation making the width 1 and 5 microseconds respectively. The signal-to-noise improvement in the receiver is proportional to the change in pulse width with modulation and to the sharpness of the pulse.

In (g), the P.T.M. multiplex is shown. In this system, the intelligence is represented by the interval between the transmitted pulse and an imaginary reference pulse. It is seen that this effect could be obtained by differentiating a P.W.M. pulse train so that a short pulse is obtained at both edges of each P.W.M. pulse. The pulse at the modulated edge of the P.W.M. pulse represents the transmitted pulse in the P.T.M. system. The pulse at the fixed edge of the P.W.M. pulse recurs at a constant rate, hence one pulse transmitted at the beginning or end of each channel sampling sequence is sufficient to synchronize the reference pulse generating circuits in the ground equipment. Thus in a system comprising n channels, a sampling cycle or frame would include (n+1) pulses, namely, 1 synchronizing pulse and n P.T.M. pulses.

An advantage of P.T.M. over P.W.M. in a given transmitter is the much greater peak power permissible with the use of P.T.M. The peak power allowable for a 1/2 or 1 microsecond pulse, as used in P.T.M., is several times greater than for the 1 to 5 microsecond pulse of the P.W.M. system. In oscilloscopic presentation, P.T.M. makes more efficient use of the available scope width than does P.I.M. In P.T.M., the reference positions of the various channel pulses are fixed and the system thus uses maximum width of scope at all times. In P.I.M., if the modulation on all channels is at one extreme, all channels are crowded into a small portion of the scope, whereas the other modulation extreme causes complete coverage of the scope width.

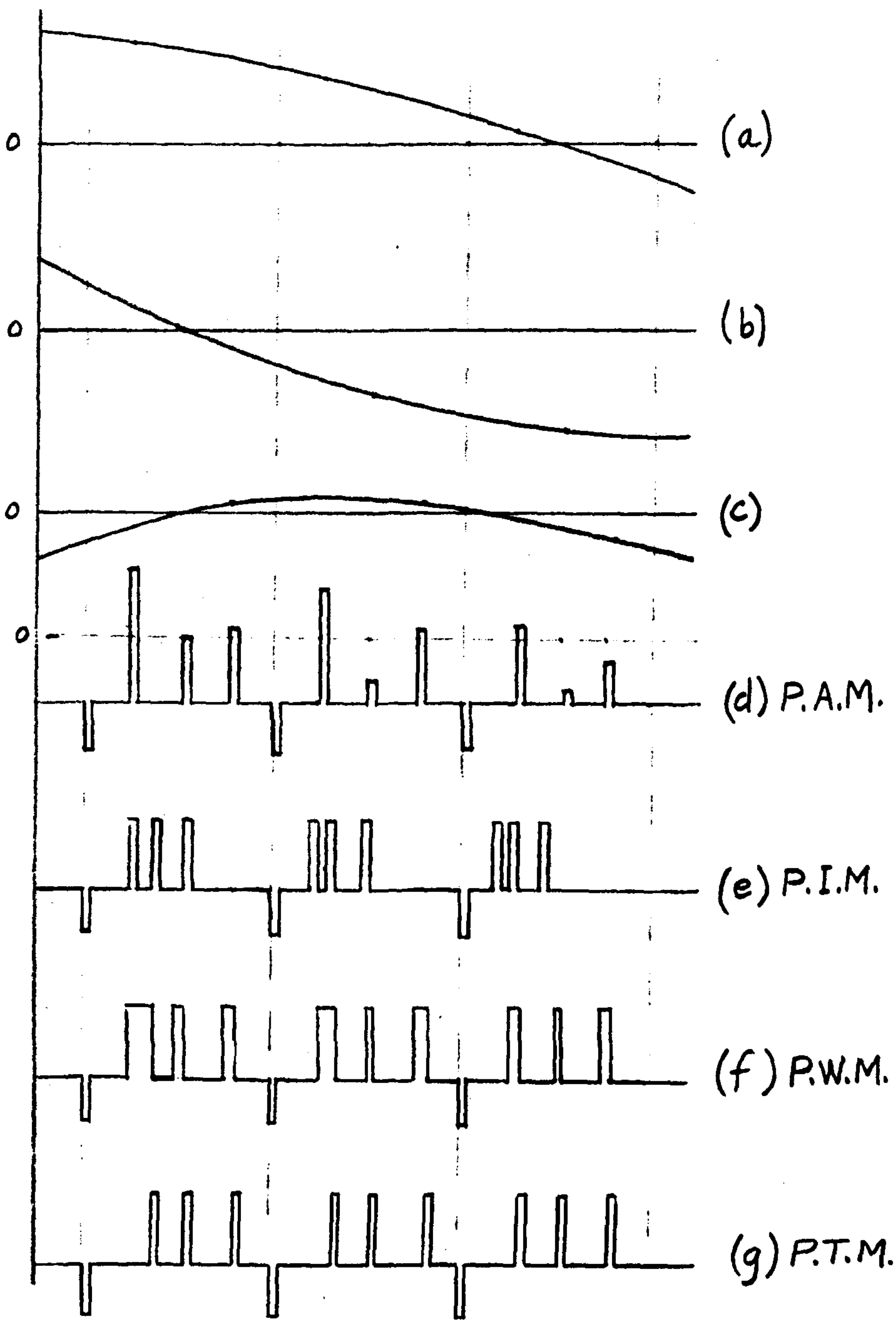


FIGURE 8. PULSE MODULATION MULTIPLEX METHODS FOR A 3-CHANNEL SYSTEM

Negative pulses represent synchronizing pulses.

Included in the transmission link are the transmitting and receiving antennas. The receiving antenna, which is usually located on the ground, has presented little difficulty because exisiting antennas, with their reflectors, have been used. Radar antennas, when cut to proper frequency, have proven satisfactory. The main considerations in the receiving antenna are directivity, size of reflector (the received energy is proportional to the square of the reflector diameter), and the ease of moving the antenna in tracking the target.

The design of the transmitting antenna entails more difficult considerations. Some of the desired characteristics are good directivity, size, and shape which do not affect the aerodynamic characteristics of the aircraft, and proper matching to the transmitter. The body of the missile often distorts the radiation pattern, but care in placing and design of the antenna, and in the location of the ground antenna, make possible patterns which direct most of the radiated energy toward the receiving antenna. Poor directivity in the transmitting or receiving antenna increases the possibility of reflections. Early in the V-2 program, the telemetering signal from the simple dipole then used was often lost when the missile rolled and the plane of polarization changed. The use of antennas which produced circularly polarized waves eliminated this difficulty. Also, it was found that a circularly polarized wave undergoes much less attenuation in rain than does the horizontally, or vertically, polarized wave.

The location of the antenna on the aircraft may also be affected by the existence of excessively high temperatures at the desired location, or by the existence of a trail of ionized engine gases which might attenuate or refract the radio wave. The antenna has often been built into portions of the aircraft tail surfaces, and in some cases portions of the body have been electrically isolated from the remainder of the structure and used as antennas. Slot antennas are particularly desirable from the standpoint of aerodynamics, and the frequencies in use are satisfactory for this type antenna.

The terminal of the transmission link is the receiver. In almost every telemetering problem, conventional receivers have been used satisfactorily. One reason that A.M. is seldom used in the transmission link is that the requirements which must be met by the automatic gain control system of the receiver are extremely severe. Any failure to maintain a constant signal level in the receiver results in error in the telemetered intelligence when A.M. is used. Other receiver requirements are automatic frequency control, good linearity of radio frequency and intermediate frequency stages, and in the case of F.M., a good limiter characteristic. The requirement of linearity to prevent cross modulation in the subcarrier system applies in the receiver as in the transmitter. Similarly, in a commutation system the transient response of the receiver must be adequate to prevent cross talk. Automatic frequency control is desirable to compensate for drift of transmitter frequency. If used in a pulse system, the receiver must have greater bandwidth and a pulse discriminator, which rejects any signal which is not a pulse of a prescribed duration, is desirable in that greater range and operating flexibility result from the decrease of random noise and undesired signals.

IV. DECODING, INDICATION, AND RECORDING

After conventional demodulation in the receiver, which separates the complex modulation signal from the radio frequency carrier, it is necessary to recover the individual channel intelligence signals, identify them with the proper channel, and deliver them to the observer in a usable form. In the case of a subcarrier system, decoding is usually accomplished by use of channel bandpass filters to separate the channel signals, followed by a detector to remove the intelligence from the subcarrier. For a commutation system, some form of commutator, which is synchronized with the airborne commutator, is necessary for the time separation of the complex signal. Upon separation, each channel signal is in its usable form, not requiring the further demodulation necessary in the subcarrier system.

1. Decoding

In this discussion, decoding is defined as the recovery of the individual channel intelligence signals from the complex modulation signal delivered to the decoder by the receiver. The complex signal obtained by the receiver upon demodulation of the radio frequency carrier should be identical with the synthesized signal which modulates the radio frequency carrier in the transmitter. Therefore, this complex signal may consist of a number of modulated subcarriers, or of a number of channel intelligence signals each occurring in succession for an equal portion of the commutation or sampling period.

If, in the choice of subcarrier frequencies, no effort is made to space the subcarriers so as to avoid the previously discussed cross modulation products, it is the design of the band pass filters in the decoder which determines the channel midfrequency spacing. The lowest subcarrier frequency is determined by the desired channel frequency response, and it is desirable, for improved signal-to-noise ratio, to keep the highest subcarrier frequency as low as possible. Therefore, to obtain the desired close spacing of channels it is necessary that the filters have sharp cut-off characteristics in order to prevent interchannel cross talk due to adjacent channel side band components. It should be noted that this type of cross talk is not the same as that introduced by cross modulation due to circuit non-linearity. In prescribing the pass band width of a channel filter, it is necessary to allow twice the highest modulation frequency component plus a small amount for subcarrier drift and change in filter characteristics.

For separation of the channel signals in a commutation system, the commutator must provide channel periods equal to those generated in the missile, and in order to afford channel identification must be synchronized with the airborne commutation system. Any of the types of commutator described in the transmission link section may be used. The received synchronizing pulse usually triggers a synchronizing pulse generator which produces a train of enabling pulses. These pulses then enable the various channels to accept information from the complex signal in proper succession and for the correct length of time. This insures that each channel will carry only that information which was delivered through the corresponding channel in the aircraft.

The demodulation of a subcarrier is accomplished by conventional methods. The resulting signal voltage is amplified and fed to the indicator circuits. Where pulse modulation is used, a pulse discriminator usually precedes the commutator, rejecting unwanted signals and reducing receiver noise. If P.W.M. is used the pulse discriminator is less effective than in the case of a system employing constant width pulses. This is because a wider tolerance must be allowed in order to pass the varying width pulses, and this allows the passing of a greater variety of noise and other undesired signals. The conversion of intelligence from a variable interval or amplitude into a variable width pulse provides a convenient form of signal for driving the indicator circuit. For example, in the first Naval Research Laboratory pulse system, in which P.I.M. was employed, the varying pulse spacings were converted into pulses the width of which varied in accordance with the pulse intervals, hence with intelligence. This variable width pulse was then used to control the charging period of a condenser, thus producing a peak voltage proportional to the intelligence being metered.

2. Indication and Recording

In applications in which it is desired that the telemetered information be available for direct observation during the flight of the aircraft, use is made of conventional indicating instruments and meters. The information is delivered to the indicator circuits from the decoder, is amplified and changed in form as necessary to proved a suitable signal for operation of the meter. The meters used are usually calibrated directly in terms of the quantity measured. The applications requiring visual indication during the missile flight are comparatively few in view of the fact that most quantities telemetered require considerable analysis before information of any value is recovered. Therefore an accurate record of the telemetered information is necessary.

Several methods of recording this information have been devised. The principal types in present use are photographic, oscillographic, and magnetic wire recorders. The phonograph type disc recorder has been used but close control of disc speed during cutting and playback is necessary. Recorders of this type and of the magnetic wire or tape type are generally used as auxiliary recorders to prevent loss of records in case of failure of the primary recorder. They are not suitable as primary recorders because the signal as recorded by them is not in a form which permits direct analysis. If the primary record is lost due to failure of the primary recorder, it is only necessary to play back the secondary record through a properly functioning primary recorder at any later time and the desired primary record is produced. The primary recorder is usually photographic or oscillographic in principle because these types can provide a graphical representation which makes data reduction possible.

The reduction of data is the bottleneck of the telemetering process. At present it is done by human agents, and long hours of tedious work are necessary to provide the data obtained in a form suitable for analysis.

Photographic recorders may employ motion picture or still cameras. In some restricted applications a motion picture of a panel of meters provides the record, but this method is not suitable in a system employing a large number of channels and measuring rapidly varying quantities. The most useful photographic method for high performance systems consists of a cathode ray tube indicator which is photographed continuously by a camera. Each channel is represented by a spot on the scope face, and the motion of the photographic film, moving at constant speed past the lens, introduces the time coordinate of the graphical record. This method produces an excellent record as used in the Naval Research Laboratory's latest system. A single photographic film is used with two lenses, side by side, each lens covering half the scope width and focusing its half of the scope presentation on one half of the moving film. The type of modulation used, P.T.M., is well adapted to this method of presentation, and a record resembling an oscillogram is obtained, with time and data reference lines being easily produced on the record. The use of the cathode ray tube indicator eliminates the inertia effect which limits frequency response in a mechanical indicator of the meter or galvanometer oscillograph type.

Recording oscillographs in general employ a series of galvanometers, one per telemeter channel. Each galvanometer has a small mirror attached to its moving element, and this mirror, moving in accordance with channel intelligence variations, directs a beam of light through an optical system to expose a spot on a moving film. The linear rate of motion of the film and the lateral movement of the light spot across the film provide a graph of measured quantity versus time. The galvanometers have a definite frequency response characteristic, and their inability to follow the higher beat frequencies produced by adjacent channel cross talk is a factor which may reduce the attenuation characteristic requirements of the channel bandpass filters.

The information which appears on the telemeter record must include not only the value of the measured quantity, but reference information as well. This reference information is inserted into the intelligence signal in the missile, and usually indicates the extremities and the midpoint of the measurement range, although in some cases other points are indicated. The reference signals are furnished in some cases by batteries, in others by oscillators, depending on the type of modulation used, and at regular intervals are inserted momentarily into the complex signal. By calibration shortly before flight, the reference signals are brought into agreement with the conditions of measurement to be represented. The calibration process varies widely among the various systems, but is in most cases involved and tedious. The reference signals are absolutely necessary, however, in that they provide the means of evaluating the telemetered variable.

V. CONCLUSION

The great variety of measurement types required in P/A telemetry and the advancement made in the art as a result of the urgent nature of the pilotless aircraft and guided missile programs have helped to produce a service which has many other commercial and military applications than those discussed in this paper. Probably the principal commercial uses are, as in the early days, in power company distribution and control systems. Any function requiring remote indication of information, such as temperatures in metallurgical processes and conditions in distant sections of mines, may make use of telemetry, although wireless transmission may not be required. The meteorological and aircraft testing applications are military as well as commercial in nature. Other military applications, present and future, include the telemetering of information from gun-fired projectiles, from remote automatic weather stations, from upper-atmosphere research missiles, from pilotless scouting missiles, and from satellites.

Some of these applications imply that the telemetering equipment will be used under combat conditions. As a communication system carrying military information, it is probable that some form of countermeasure will be employed either to jam the system or to inject false information into it. The principal countermeasures target during the last war was radar. Enemy communications systems were generally unmolested in the hope of gaining useful information from them, but because a telemetering system might be carrying information harmful to the enemy, it is likely that countermeasures will be used. In comparison with radar, telemetering is more difficult to jam from a power standpoint because the received signal is direct from a transmitter whereas in radar it is a very weak reflected signal. An outweighing disadvantage, however, is the fact that a much higher signal-to-noise ratio is required in telemetering for accurate data recovery. Future development of equipment should include incorporation of countermeasures features.

In telemetry, as in other technical fields, the economic and logistic advantages of standardization are obvious. It is also obvious, however, that the great diversity of telemetering requirements in the various P/A developments, both present and future, make the problem of standardization extremely difficult. Not only do the types and ranges of information to be measured vary greatly in the different projects, but the weight and space limitations, the range and power, the accuracy, and the channel requirements are seldom similar. Aside from these factors, availability of critical parts and tight time schedules often make the use of nonstandard equipment imperative. In the standardization plan recently formulated by the United States Navy, four airborne equipments and one ground station were selected to provide telemetering services of "medium" or "high" performance, with regard to information handling capacity, in small, medium-sized, or large missiles. The systems to be used, classified as above, are shown in the following table:

	Size of Vehicle		
	Small	Medium	Large
Medium Performance	AN/UKR-5	AN/AKT-10	AN/AKT-10
High Performance	AN/DKT-1	AN/DKT-1	AN/AKT-11A

Both medium performance systems are of the frequency modulated subcarrier type, while the high performance systems employ pulse modulation. The ground station, comprising three receivers with a common recording and indicating system, is designed to be capable of use with any of the four airborne units.

The greatest danger of standardization is the possibility of slowing down or stopping advancement in the art. This stagnation may be combatted by the letting of study and development contracts whose objectives are to improve existing methods and to investigate and develop new methods, and by maintaining a flexible standardization whose efficiency, suitability, and adaptability to the telemetering requirements of the P/A program are periodically examined.

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