A MULTICHANNEL SINGLE FREQUENCY RADIO CONTROL SYSTEM

by

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A MULTICHANNEL SINGLE FREQUENCY RADIO CONTROL SYSTEM

CHAPTER 1

INTRODUCTION

In recent years the Federal Communications Commission has opened the 27.255 MC and 465 MC radio bands for public usage. These citizens' bands, as they are called, must be used with registered transmitters. However, it is not necessary for the operator to pass an examination, as has been the case in the past.

The opening of these bands has resulted in widespread usage of radio control and there are an estimated quarter million transmitters operating on these frequencies at the present time. With the increased use of radio control there has arisen an increasing demand for multichannel equipment on these frequencies for greater controllability.

Commercial suppliers of radio control equipment on the citizens' bands have been able to meet these demands to a limited degree but with certain performance failings.

The more successful commercial systems will be examined for the essential features of a good multichannel radio control system. Various other systems of merit will also be considered. The objective is to combine the desirable features of several basic systems into a multichannel radio control system which will meet all of the desired criteria of a good radio control system.

To date, two-channel radio equipment is available from several manufacturers and is quite reliable. There is also equipment available for up to eight channels; however, with more than three channels, the equipment requires frequent maintenance, is very costly, and requires an experienced operator. Moreover, only two of the eight channels may be used at the same time. Obviously, there is much to be desired in the available radio control systems. What should a desirable system feature? Can the available equipment and designs be improved upon?

The latter question will be discussed in subsequent chapters; as to the first, it may be answered best by considering what there is to work with and to what uses the system may be put. The more desired features are listed below and each will be examined in detail. It should be remembered that these will apply for any single frequency system, whether or not on the citizens' bands.

1. A competitive price
2. Light weight
3. Single radio frequency operation
4. Interference resistance
5. Ruggedness
6. Ease of operation
7. Small size
8. As many channels of control as possible

Competitive Price

Since the citizens' bands were provided to give radio control to the masses, small businesses, and other similar applications, any system developed must provide not only substantial improvements over existing equipment but must not be complex and prohibitively costly.

Light Weight

There are many aircraft applications, and the radio control of model aircraft is the greatest market for equipment at this time. Applications such as these will require very low total receiver weights if the system is to be acceptable.

Single Radio Frequency Operation

Operation on either of the two frequencies allotted by the Federal Communications Commission requires a permit. For organizations and businesses which can show proper need, the Federal Communications Commission will allot examination-free frequencies other than the two citizens' bands, but in any case desirable control must be achieved on a limited number of radio frequencies. It may be possible in some cases to make use of the large quantity of equipment already on the market without modifications.

Interference Resistance

One of the disadvantages of using a citizens' band is the interference due to the large number of operators. The Federal Communications Commission has limited the input power of transmitters used on these bands to a five watt maximum in an effort to reduce this interference. Traffic signals in metropolitan areas are being operated during rush hours and emergencies by radio control. Moreover, the five watt power limit does not apply in these instances. Add to this an estimated quarter of a million privately-owned transmitters and there are serious interference problems. A good system, therefore, should be able to reject extraneous signals, or recover quickly from the disturbing impulse.

Ruggedness

Citizens' band equipment must not be fragile. It is intended for use by the layman as well as the professional and the layman's only concern is whether it will work and keep working. Equipment designed for such versatile applications must be able to take the jolts the public will most certainly deliver.

Ease of Operation

Since the equipment would be available for general use, its operation should be as simple as possible. If too complex, much of its wide appeal and usefulness will be lost.

Size

A good system would be compact and easily installed, especially where space is at a premium. Present five and eight channel units are extremely compact, and any competitive system should not have appreciably more volume.

Channels

All of the above criteria are affected adversely by an increase in the number of channels, yet there must be a number of such channels of operation if more than one task is to be controlled by radio. The question, then, is how many channels? Each application will dictate this requirement, and it would be nice if one could design for each case. This of course is economically unsound. A maximum of eight channels are now available commerically and with certain compromises which will be discussed later, it is possible to obtain radio control systems having only the number of channels necessary, provided no more than eight are required. For more than eight channels there is no choice, for there are no commercial systems available on the citizens' bands which provide more than eight channels.

The desire for more channels was strong, and as commercial equipment became available new uses for radio control were found and even more channels desired. It was this process that lead from the original single channel equipment to the present eight channel equipment. Again model aircraft radio control users are responsible for this effort to obtain more controllability. They represent all but a very small percentage of the over a quarter million citizens' band operators. They were responsible for the industry's development of the present eight channel equipment.

The requirements for a multichannel single frequency radio control system have been mentioned and are stringent in themselves. It can be seen that the weight, size, ease of operation and cost are very severe limitations when applied to model aircraft. Moreover, the requests of a quarter million consumers are not easily ignored. Fortunately, a system suitable for model aircraft and meeting the rest of the design criteria will be suitable for even more varied uses and will be conservatively designed.

In view of the increasing need for more control, ten channels should be a minimum. Any new design should be easily adapted to increasing the number of channels above ten, as future needs and demands arise.

A radio control system with ten or more channels of control is now desirable. Operation should be on only one frequency if advantage is to be taken of the citizens' bands, and there is no way to obtain more than one channel except by coding the transmitted signal in some manner. Moreover, this system must have stability, inherent ruggedness, light weight, and small volume.

In the following chapters, basic methods and typical systems are considered, keeping in mind the foregoing criteria. All of the systems discussed are found lacking in one or more of the features considered essential. The meeting of these requirements necessitated the design of a new system and some of the more desirable features of the systems under discussion have been incorporated into this new system.

CHAPTER 2

CODING METHODS

In finding a suitable control system all the design criteria in the foregoing chapter must be kept in mind; however, consider at this time only methods of obtaining more than one channel of operation from one radio frequency. This is perhaps the most critical feature, as all the other design parameters will limit themselves accordingly.

It has already been mentioned that the only method of obtaining multiple channels on a single radio frequency is through a coded signal, and there are several means of doing this, i. e. amplitude modulate, frequency modulate, and pulse modulate. All three may be combined in any manner. Their combinations and decoding techniques will be considered later.

Amplitude Modulation

Consider a radio frequency carrier amplitude modulated with two different audio frequencies, 2500 cps and 4000 cps. If each audio frequency carries different information there will be two distinct channels, since information on 2500 cps will not be observed by the 4000 cps circuit and conversely. There may now be as many such channels as required by simply adding additional audio frequencies for each desired channel of operation.

Varying Signal Strength

This method allots a given signal strength to given information. To perform a control function requires that a signal voltage at the receiver of a fixed amount operate that function. Since the signal strength of the transmitter can be controlled, any number of such channels can be obtained.

Pulse Codes

Certainly there is no limit to the number of ways in which the carrier may be interrupted or pulsed. Therefore, these pulsing methods must be classified into types for clearer analysis. The question, in what ways may the carrier be interrupted, immediately arises.

1. Varying pulse width, constant period- Varying the time width of a pulse of energy from the transmitter amounts to merely turning on the carrier for a specified portion of the period. One control function may now be allotted to a certain degree of of asymmetry. Assigning different ratios to different functions will give the required number of channels.

2. Numerical sequence- If the signal is transmitted in short pulses of energy, these pulses can be simply counted. For example, let nine pulses represent

one function, seven another, and so on. Thus, by allotting ten pulses one may have ten separate functions.

3. Sequence (pulse presence or omission)- Consider a unit which will send ten pulses of constant width and spacing. With the foregoing numerical system it was possible to have ten different functions corresponding to 1, 1-2, 1-2-3, 1-2-3-4, etc. There are many more combinations than this, however, and if the system senses a pulses's presense or absense in its proper sequence, the number of possible channels is greatly multiplied. A method of indicating the beginning of each cycle by means of an abnormal pulse length for example will complete the system. However, if the coder cycles through a fixed and known time period, it will also know when the cycle begins. It can be seen that the possible number of combinations are 1 + n!, where n is the number of possible pulses per cycle. Thus, a ten pulse system has 3,628,801 combinations!

4. Varying rate- The methods of orienting the pulses and spaces have now been covered; however, another thing may be done to the pulses. The rate at which the pulses are sent can be varied. This applies to all of the previous systems. Assigning different repetition rates to different functions will allow distinct channels of operation. Note that the numerical and pulse presence systems, excepting the latter's

continuous cycle modification, may incorporate this feature as an addition without impairing normal operation.

CHAPTER 3

AUDIO FREQUENCY DECODERS

Tuned Reeds

Every bar of metal has an infinite number of fundamental frequencies determined by its support, shape, loading, and material. When such a beam is excited at its lowest natural frequency, the amplitude of its oscillation is greatest.

The thin ferromagnetic reeds of Figure 1 are trimmed to various lengths in order to provide different natural frequencies. The fundamental frequency of each reed must not be a multiple of any of the other frequencies. This frequency should not be too high, for a pliant reed with its larger amplitude at resonant frequency is desirable.

Reeds of substantial length are cantilever mounted over one pole of an electromagnet, the reed itself being the other pole. The coil of this magnet is connected to the output circuit of the receiver.

Let 256 cps be one of the control frequencies with which the carrier is modulated. The signal is received, demodulated, amplified, and delivered to the load which in this case is the bank of reeds. There is now a 256 cps excitation force applied via the electromagnet to the reeds; this force is too small in

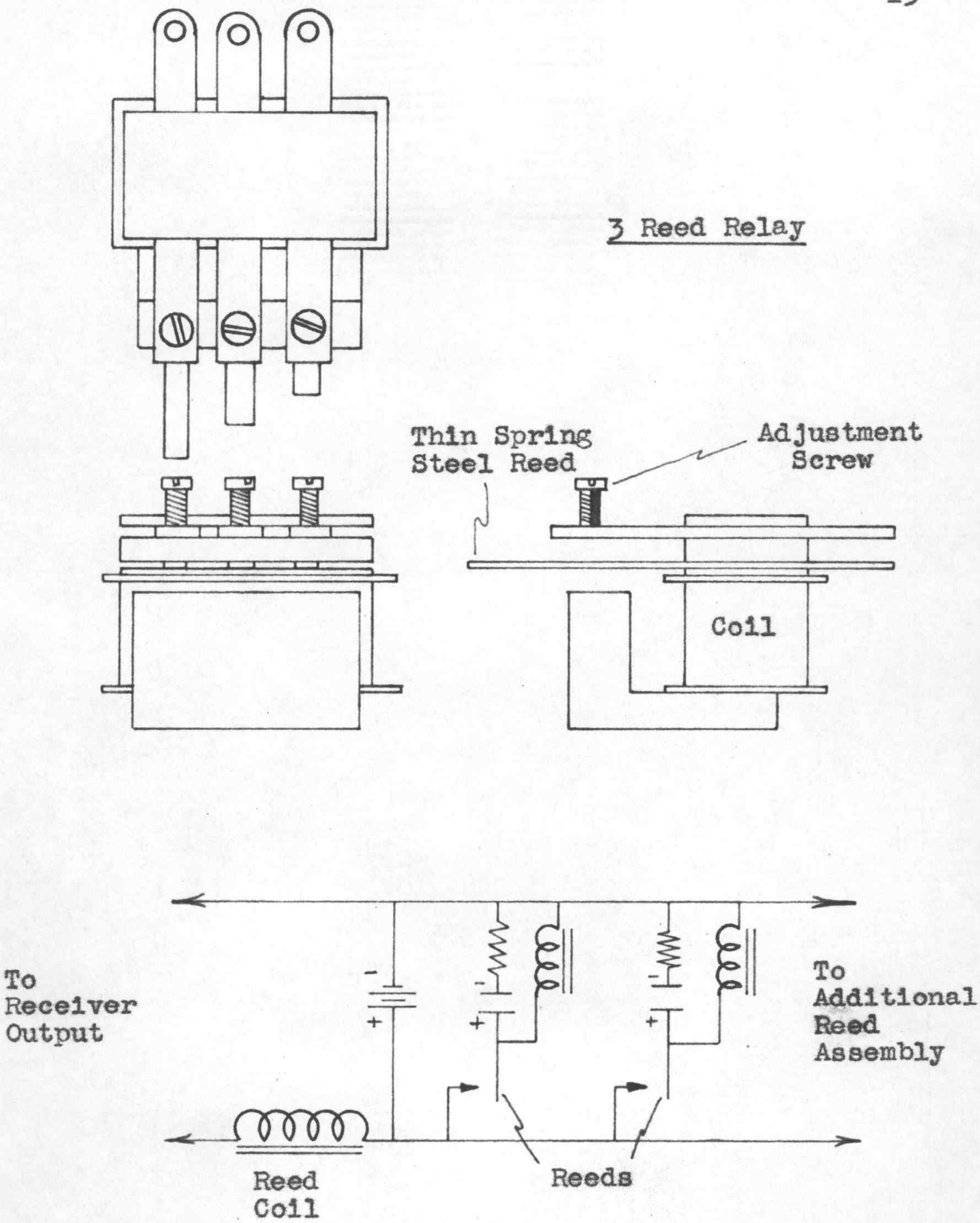


Figure 1

Reed Relay and Circuit

itself to cause any significant deflection and is generally sinusoidal. A reed that is to represent this particular channel is now trimmed in length until resonant frequency is reached as indicated by large deflections of the reed. The reed contact screw is than adjusted until the reed makes contact once each cycle and intermittently supplies power to its particular relay. The capacitor in the relay circuit must store sufficient energy to keep the relay closed while the reed is open. Whenever the proper tone is received the reed will vibrate and close its relay.

It would seem that a number of channels are available; however, there are several problems. Figure 2 displays a typical frequency response curve which indicates that there is not a sharp peak at resonant frequency but rather a band of frequencies (20,p.83). This band width is a measure of the selectivity of the reed bank. Since each reed responds to a band of frequencies it becomes increasingly difficult to assign frequencies which will not be multiples of one another. In fact, for the example frequency of 256 cps the upper limit must be its first overtone, 512 cps. In addition to this, there exists the problem of tone stability in the transmitter, made more difficult by the need for small size and portability. These problems can best be handled by maintaining a sufficient gap between tones.

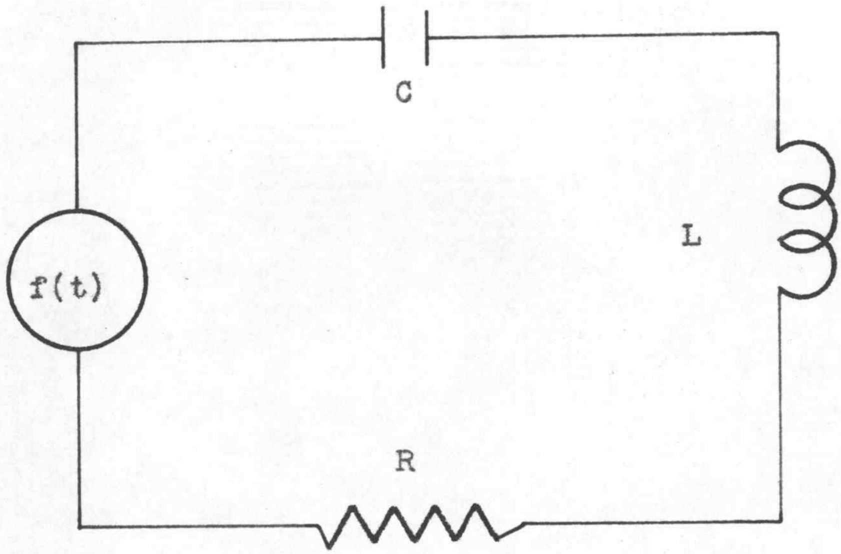
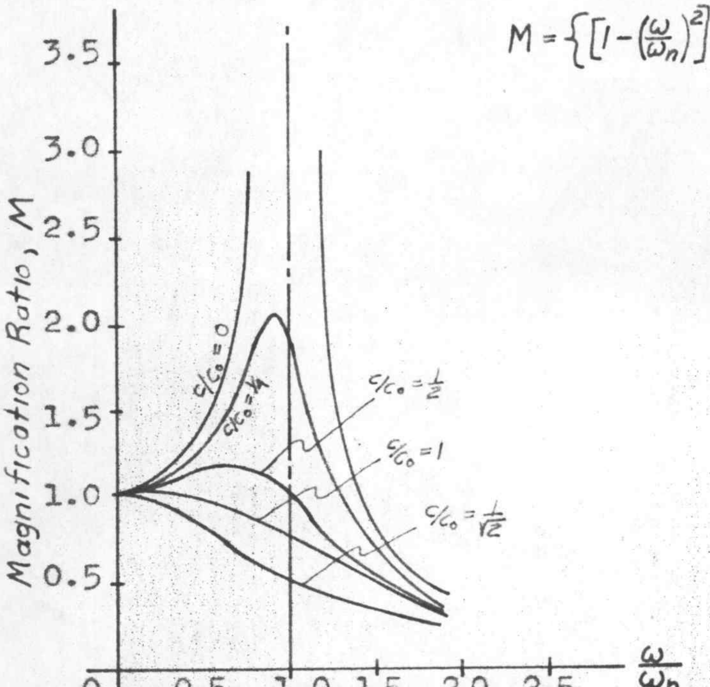


Figure 3

R-L-C Circuit



$$M = \left\{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\frac{c}{c_0}\frac{\omega}{\omega_n}\right]^2\right\}^{-1}$$

and is the factor by which the static deflection produced in the reed of modulus K by a constant force F_0 acts dynamically with frequency

c/c_0 = damping ratio
ω/ω_n = frequency "
c_0 = critical damping
ω_n = Resonant frequency

Figure 2

Response Curve
(20, p.83)

The reed receiver has some very good points. Its complete audio frequency discriminating system is the reed bank itself. At present eight reed units weigh as little as an ounce and are available from several commercial sources. Within the past six months several companies have made available complete nine ounce, eight reed, radio control systems with four pound hand held transmitters. These advances have been achieved primarily through improvements in tone stability. One also has a semi-simultaneous system in the new eight reed units, in that the channel separation is so small that one may select a frequency between any two reeds and excite both. There are still no more than two channels available at one time. Furthermore, simultaneous operation of all channels is not possible. Reed receivers are also known to be prone to failure due to pitted reed contact points. The specifications for a typical eight reed receiver will be found in the Receiver System Specifications in the Appendix.

Band Pass Circuits

Audio frequencies may also be separated by other means. An electrical analog of the mechanically vibrating reed may be employed. An example of such is an R-L-C circuit as shown in Figure 3. Let f(t) represent the audio frequency current to be passed and to represent the control function. Function f(t) is normally sinusoidal and represents the receiver output.

At the resonant frequency the impedance to f(t) is a minimum, and the largest current flows. If the voltage drop across R is now plotted against frequency, Figure 4, a peak will occur at this resonant point. E_R is now applied to the grid of a vacuum tube which has been biased to cut-off. When E_R exceeds the bias voltage, plate current will flow and operate the plate circuit relay. All frequencies other than the resonant frequency have no effect; only the resonant frequency can cause its particular channel relay to pull in. Adding additional R-L-C circuits, one for each audio frequency channel, will complete a multichannel tone system. Comparing the E_R versus frequency curve with the amplitude versus frequency curve on the reed system will verify the similarity of the two systems.

Note the slope of the E_R - frequency curve as resonance is approached. If the relay tube is biased marginally to allow only frequencies very close to the resonance frequency to initiate conduction, drift in frequency will cause trouble. This problem may be alleviated by selecting a certain band width with the center frequency representing the control function. The components in the R_1-L_1-C_1 circuit are now adjusted

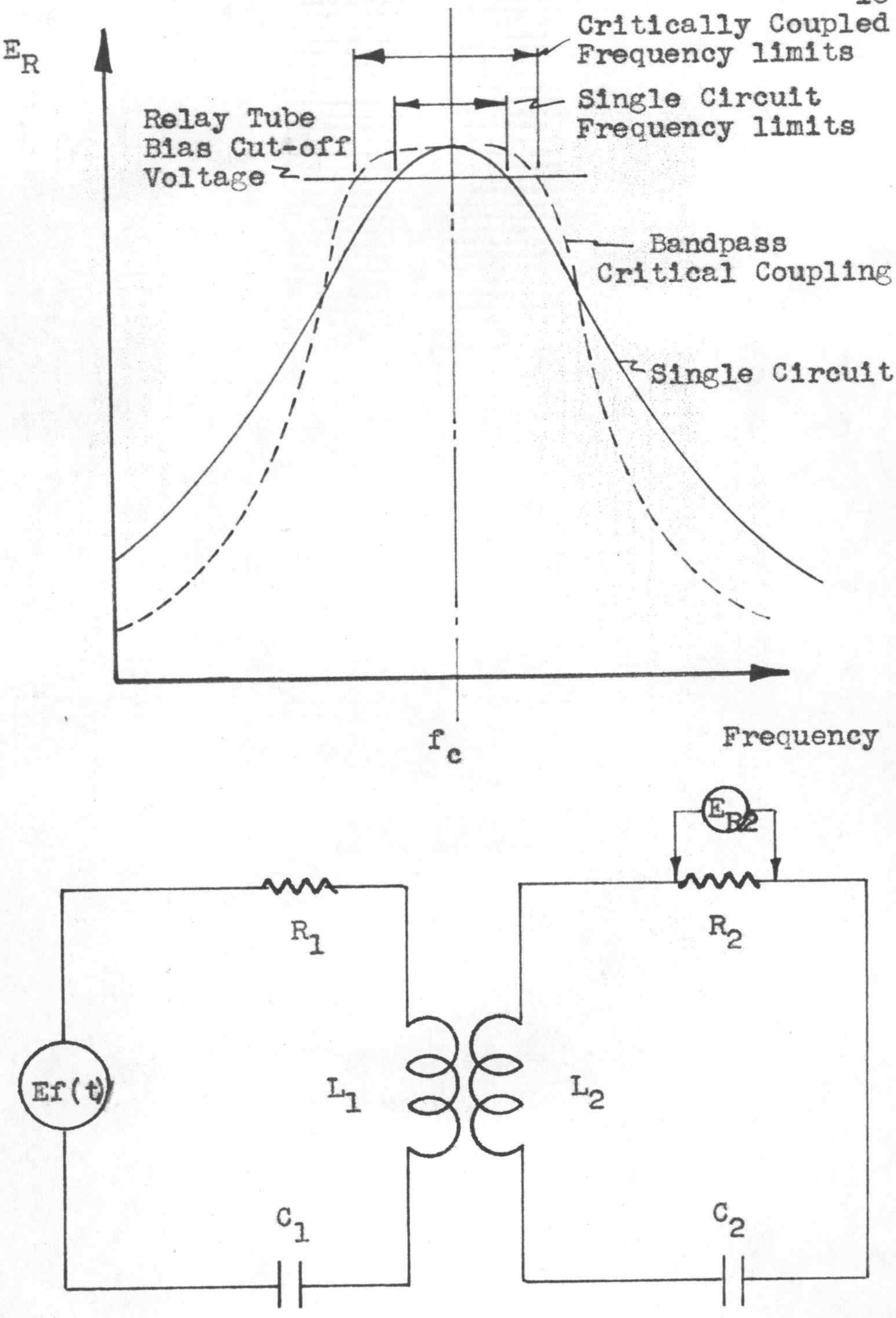


Figure 4

Response of a Double Tuned Critically Coupled Circuit,

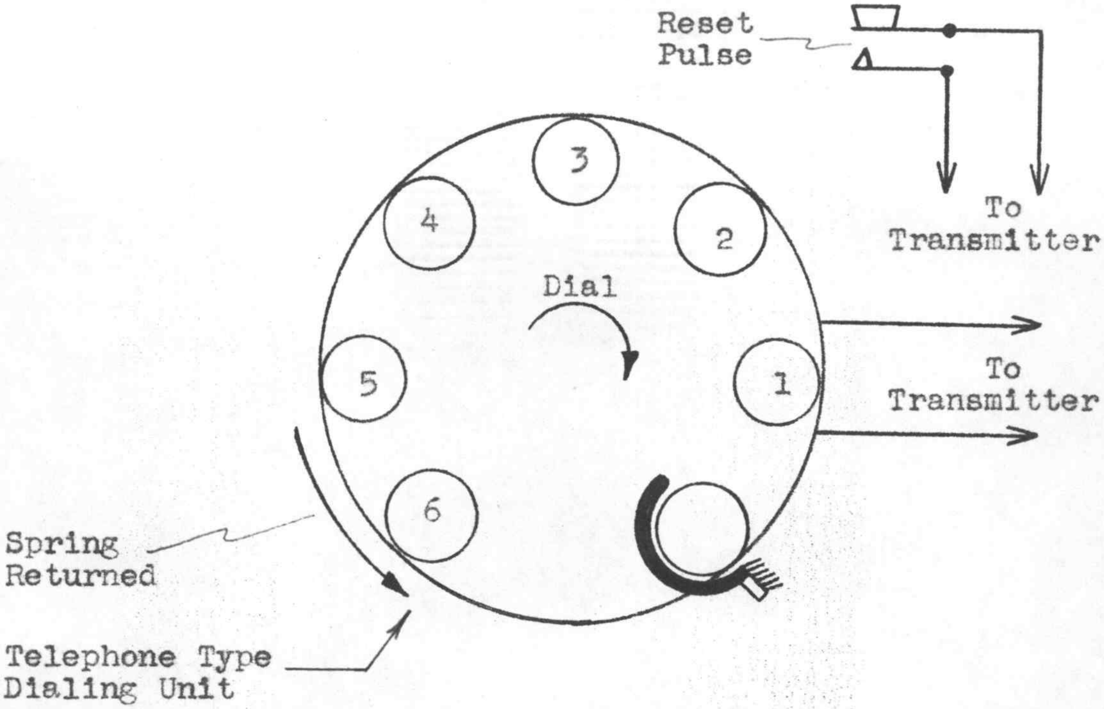


Figure 5

Numerical Sequence Code

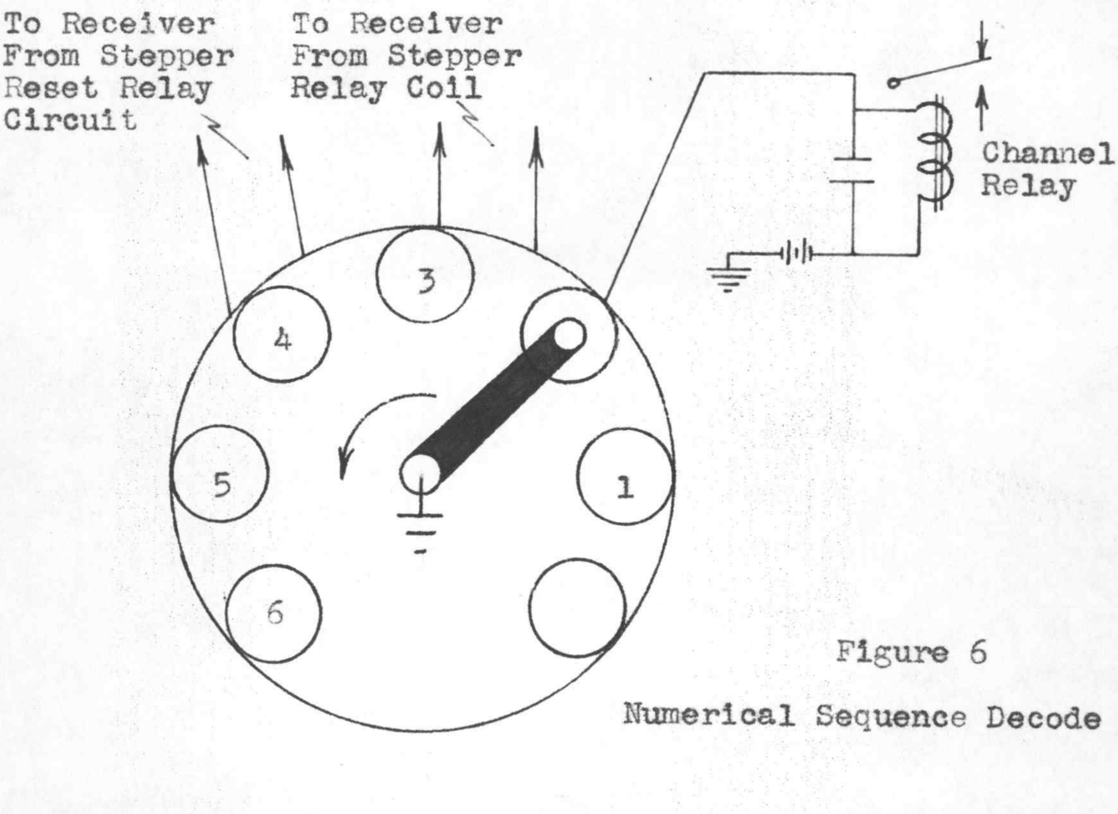


Figure 6

Numerical Sequence Decode

so that its resonant frequency is the lowest frequency of the specified band width. Now another R_2-L_2-C_2 circuit is critically coupled and turned to the upper most frequency of the desired band width. It will be found that E_{R2} versus frequency has a greater slope and a flattened peak, Figure 4. This circuit will be less critical, giving good results so long as the transmitted channel frequency stays within the band width. There may be other audio discriminating methods; however, the methods discussed are typical and popular at this time because of their basic simplicity and reliability.

Bandpass filter circuits have some advantages over reed systems. They have no moving parts and, when coupled circuits are used, they are more tolerant of frequency drift and adjustment. Maintenance problems are almost non-existant, and there are no electrical contacts to pit and cause erratic operation or failure as with reed systems. The bandwidth and harmonic problems are still present as are the other reed difficulties; however, higher audio frequencies can be used to alleviate the former since mechanical limitations do not exist. Inductors tend to be larger and heavier than reed banks; except for this they would be used rather than reeds, and for weight-tolerant or two or three channel applications they are considered superior. Typical bandpass receiver specifications are shown in the Receiver System Specifications of the Appendix.

CHAPTER 4

IMPULSE DECODING

Varying Amplitude

Assigning different amplitudes for each control channel has one serious disadvantage. The amplitude or signal strength is a function primarily of the transmitter output, which can be controlled, and of the distance the receiver is from the transmitting antenna. The receiver has no way of telling whether the signal level has changed or whether the transmitting distance has changed. The seriousness of this problem when considering such a system for use in aircraft should be obvious. The system is useful where the code units are connected by wires, however.

Numerical Sequence

A typical numerical sequence system is the telephone dialing unit which may be directly adapted to radio. Figures 5 and 6 show such a coder and decoder. The coder will key the transmitted carrier, the receiver will pick up the pulsed carrier and deliver it to the decoder. The decoder is a stepping device which is indexed one step each time it receives a pulse. A reset-pulse must be employed to return the stepper to zero following each command. This may be two short pulses, a pulse of longer duration, or any other method which will not become confused with the normal coding pulses. When the coder is spring returned and speed governed, as is a telephone dialing unit, the pulses are sent at a steady rate with constant pulse duration and separation. By making the reset relay a time delay relay, with delay time slightly greater than the normal pulse width, reset to zero may be made at any time by keying the transmitter with a pulse of proper duration.

When a control position is selected, seven for example, seven consecutive pulses will be sent. The stepper rotates as the pulses are sent, stopping on the seventh pulse at position seven. If delay relays are connected into the stepper position circuits for use as the control relays they will not operate until the stepper pauses at the desired channel.

With a numerical system of this type a large number of channels are available; however, since it must cycle from zero on each control, there will be substantial delay until the control function begins. There is no provision for simultaneous control. While a number of channels are possible, the operator must return the controls to neutral after each function and before another command may be given. The specifications of a typical unit may be found in the Receiver System Specifications of the Appendix.

Varying Pulse Width

A small, circular, permanent magnet is mounted between the poles of the electromagnet shown in Figure 7. As the direct current source is applied to the electromagnet it will cause the permanent magnet disk to rotate until it reaches the stops. Reversing the polarity causes the armature to rotate in the opposite direction against the other stop. As long as a pulse is not received, the armature remains against the stop, since the double-pole-single-throw relay is open. When a signal is received, the relay pulls in and the armature rotates against the opposite stop. If the pulses are transmitted with a given period of equal on to off time, the armature will be against one stop just as long as another. Increasing the pulse rate to about twenty pulses per second and damping the armature shaft will result in the armature centering itself half way between the poles. The armature will remain here so long as the carrier remains on fifty percent of the time and off fifty percent of the time. Varying these percentages will result in smooth proportional control of the armature position. Other actuator types will give such control on rates of as little as five cps; these actuators are commercially available and weigh approximately one ounce, their size being determined by the shaft load required.

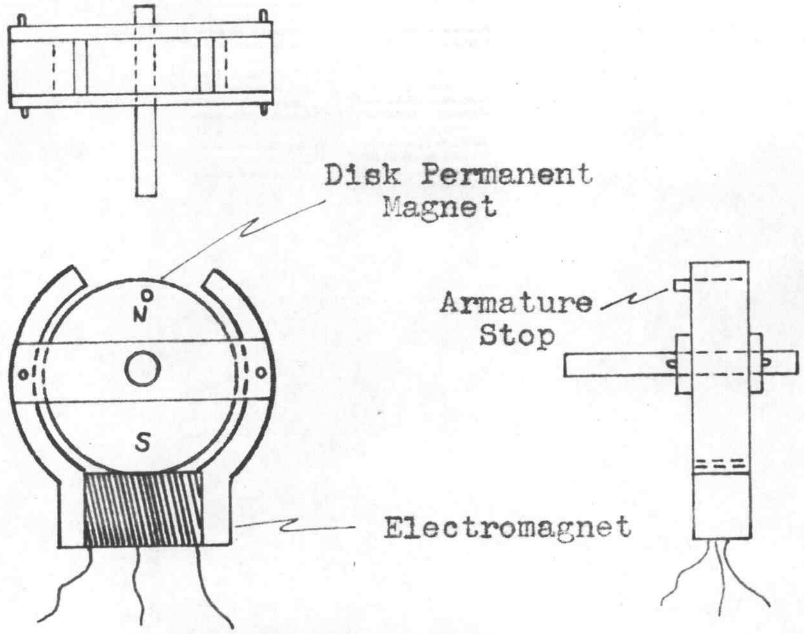


Figure 7

Proportional Actuator

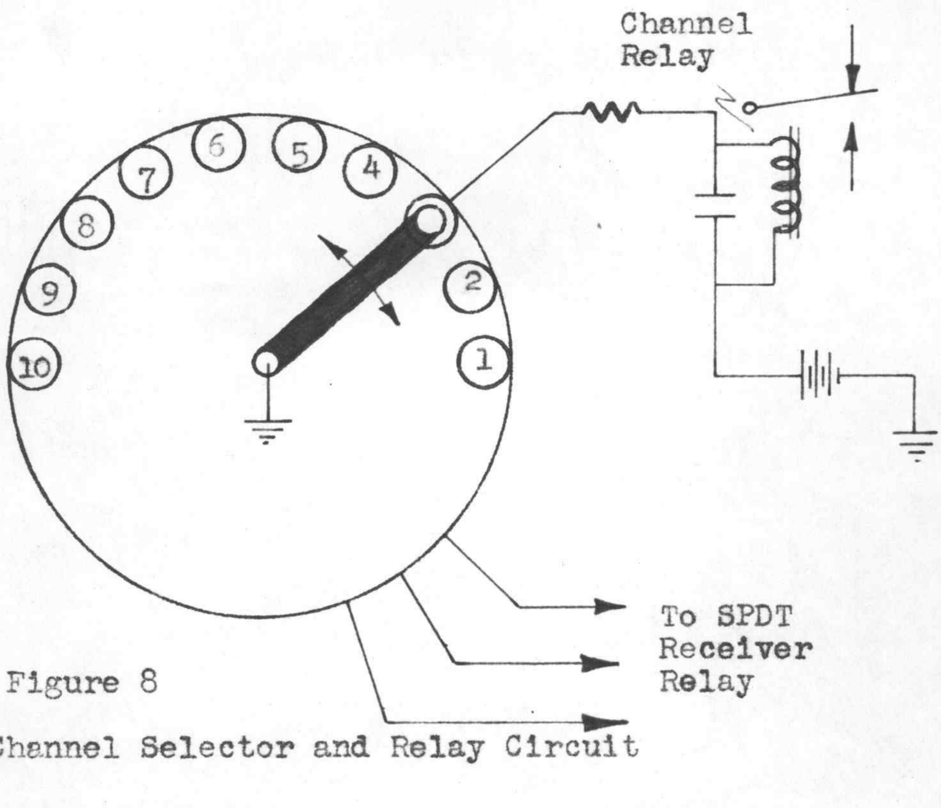


Figure 8

Rotary Channel Selector and Relay Circuit

Generally, the actuator is attached directly to the controlled device and the system is carried no further; however, very often proportional control of this degree and only one channel is not desired. This unit may than be used to increase the available number of channels.

Attaching the actuator to a commutator, Figure 8, exactly like the one used in the foregoing numerical sequence unit, Figure 6, as many channels may be had as there are contacts. The contacts may have to be arranged other than uniformly around the circle, since the rotation of the actuators is generally nonlinear with respect to the pulse width; however, this should pose no great difficulties. Again, time delay relays must be employed to prevent operation of unwanted channels as their contacts are passed over. This system has two important advantages over the numerical sequence system. First, there is no need to reset to zero after each operation; second, there is no need to begin at zero each time since the next control position may be reached directly. Again, there is no simultaneous control. There can be only a few channels, about five, since the actuators do not rotate a full 360° and do not follow the pulse width with sufficient accuracy. Moreover, if the operator is slow in moving to another position, an unwanted channel may be activated when passed over. A typical system's specifications are shown in the

Receiver System Specifications in the Appendix.

Pulse Rate

A pulse rate system must provide the desired control without regard to the pulse width. Two conditions are shown in Figure 9, relay one closed and relay one open. When relay one closes, the battery sends current through the normally closed circuit of relay two and causes the actuator to rotate against its stop. This actuator is similar to that described in connection with pulse width decoding and illustrated in Figures 7 and 8. While relay one is closed, current also flows via the normally-open relay one contact through L. Note that the diode allows no current to flow through relay two. When the receiver relay opens the inductive voltage in L, being of opposite polarity to the battery, causes current to flow through the diode and relay two, thus charging the capacitor C. C then discharges through relay two, helping to keep it closed momentarily. The actuator thus rotates in the opposite direction against the other stop.

Regardless of the pulse width the impulse from C through relay two is of constant duration, so long as the pulse rate is slow enough that C has time to charge to the same voltage. Thus, at some pulserate, relay two off time will equal the impulse duration, and at some other rate the off time will be some fraction of

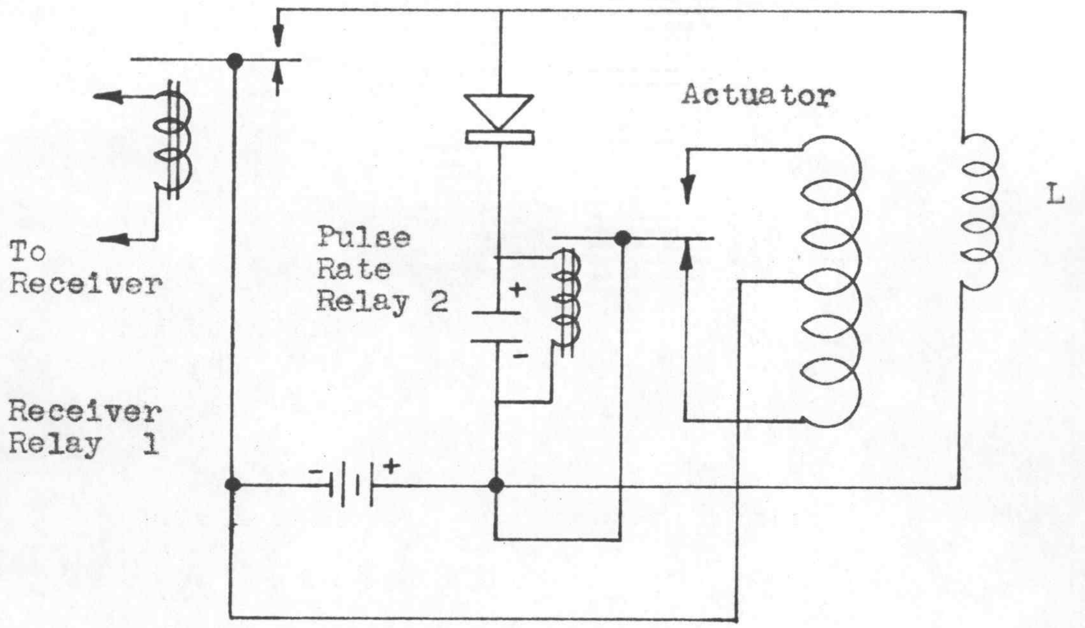


Figure 9

Pulse Rate Circuit, (18, Vol., p.32-33)

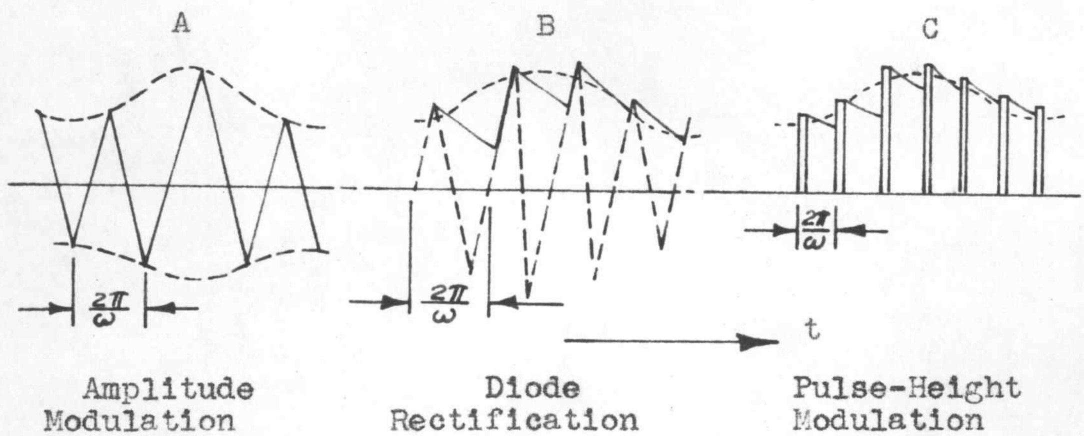


Figure 10

Diode Detected Modulation Envelopes,

the impulse duration, The actuator will, therefore, respond identically to the actuator in the previously discussed pulse width system, and it may be used in the same capacities.

A pulse width system may be had by making L the coil of another actuator. However, relay two operates the pulse rate actuator which is uneffected by any change in pulse width. Since relay two responds to pulse rate and relay one affects L by pulse width both systems may be operated simultaneously. The same problems exist with this system as with the pulse width method. While dual proportional actuators are now used, the unit supplying the inductive voltage is rather large. This system is difficult to set up properly and the actuators follow with even less accuracy than with pulse width systems. Further, since the system operates on pulse rate, it is no longer possible to damp out the actuator oscillations. It is for these reasons that this system is used only for two channel purposes requiring a high degree of control. This system has been in use since 1954 and specifications are shown in the Receiver System Specifications in the Appendix.

Pulse Modulation

There are three forms of pulse modulation- height, width, and position. Each has its own peculiarities;

however, it will suffice here to deal with but one representative form. Consider the relation between amplitude or wave modulation and pulse height modulation. Figure 10-A shows an amplitude modulated carrier with the dotted line representing the amplitude modulation envelope. When the carrier is rectified by the diode circuit of Figure 11, there is a voltage across the resistor, Figure 10-B. Slant lines to the right of each peak represent the decay voltage determined by the time constant of R and C. This time constant must be large compared to the period of the audio frequency for best results.

This latter requirement limits the choice of audio and radio frequencies. Practice has shown that with the proper time constant a carrier frequency of as little as 10 kc is compatible with an audio frequency of from 0 to 5 kc, which is sufficient for most purposes. While this appears to be rather marginal, 10 kc is still large compared to the lower audio frequencies. The distortion accompanying the higher frequencies will be reduced by cutting off the higher harmonics in the same filter choke used to suppress the 10 kc carrier. This reduced efficiency or "roll-off" at the higher frequencies can be corrected by proper audio compensation at the receiving end.

The entire dotted portion of the curve of Figure 12

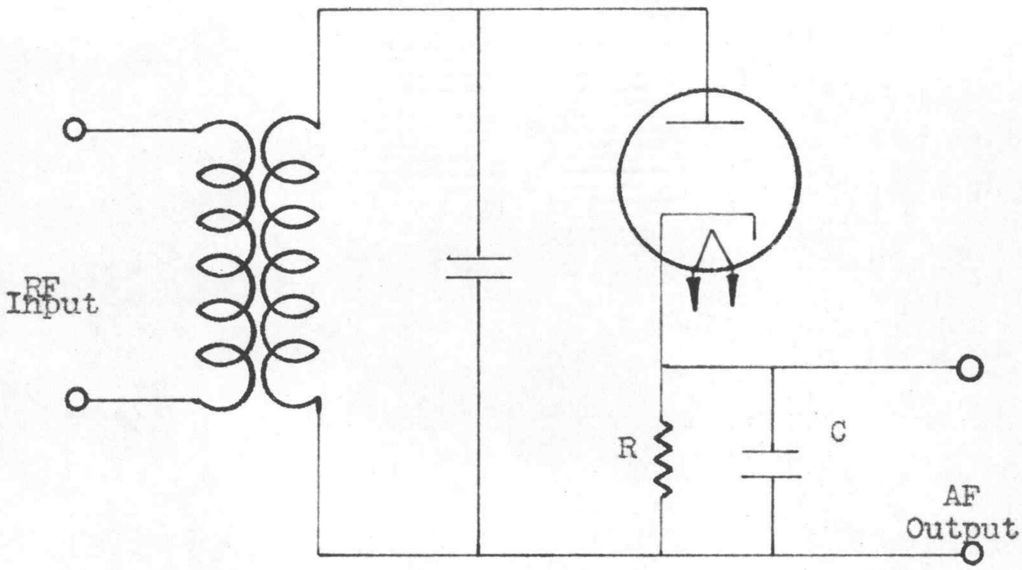


Figure 11

Diode Detector

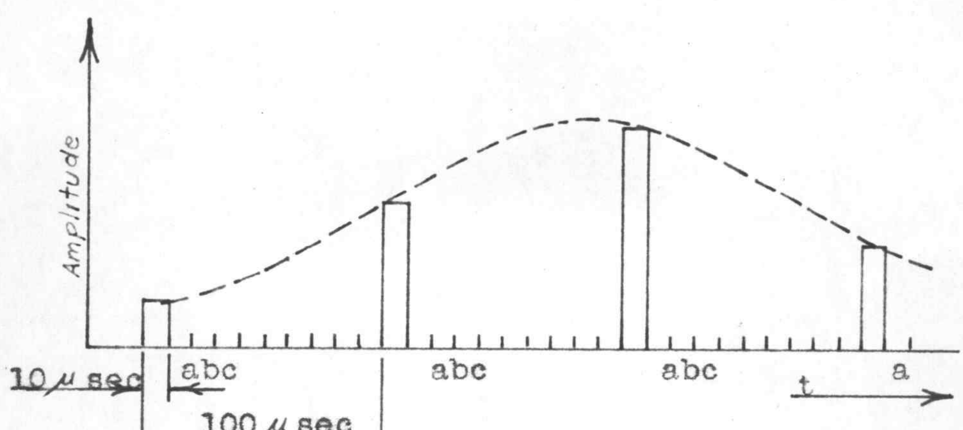


Figure 12

A Diode Detected Pulse-Height
Modulated Carrier.

could be eliminated without loss of performance. Figure 10-C shows that virtually the same result is obtained with short, positive pulses as is obtained with a wave modulated carrier. ω is now the pulse repetition frequency rather than the carrier frequency. Thus, equivalent results are obtained by pulses transmitted at 10 kc via a carrier of 465 MC. for example, with pulse height modulation. Figure 12 shows a pulse duration of 10 seconds, and a pulse spacing of 100 seconds. The dotted line again represents the audio frequency modulation envelope. There is ample space between pulses for additional pulses, each of which could be modulated in like manner and would represent another distinct channel of intelligence.

Such a system must be synchronized. Further, while it appears that there may be any number of channels, A. H. Bruinsma indicates that practice has determined a pulse width of 10 micro seconds for a 100 micro second period (2,p.1-97). With the synchronization pulse and some small spacing between pulses, no more than eight channels can be included. Gating circuits must now be employed to let through each channel pulse on each cycle at the precise moment. Such circuits while not overly complex in operation may employ more parts and circuitry than some entire systems. Moreover, there must be one such gating circuit for each channel. Presently pulse modulation systems require much more circuitry than AM or FM systems. This system does allow simultaneous operation with a control lag of only a few micro seconds. Its bulk, complexity, and weight rule it out as a desirable solution for the design requirements laid down in chapter one. Receiver System Specifications of the Appendix gives the specifications for a simplified eight channel system with one audio channel and seven relay, or switching, channels.

COMBINED SYSTEMS

Two Tone Pulse Width

Instead of sending an even wave-like audio tone, it is possible to distort the tone wave forms to those of Figure 13. Figure 13-A shows a 100 cps wave with the narrow portion rectified, and Figure 13-B shows the same wave form with the opposing wide part rectified. Figure 13-A is designated a 20/80 tone, while Figure 13-B is an 80/20 tone. A pulse width diode bridge-detector circuit is shown in the upper right of Figure 14. This circuit has the property of delivering a positive voltage at "A" for broad pulses and a negative voltage for narrow pulses. So long as the wave shape is 20/80 and 80/20 this circuit is satisfied without regard to the tonal frequency.

The voltage at "A" is led to the grid of the relay tube where for broad pulses the relay is pulled in and for narrow pulses the tube is cut off, releasing the relay. If the transmitter is switched from narrow to broad pulses at four cps, the relay will also operate at this rate, and by varying the relay dwell time the customary pulse width system is obtained.

The waves of Figures 13-C and 13-D are the same as Figures 13-A and 13-B, except that the frequency is

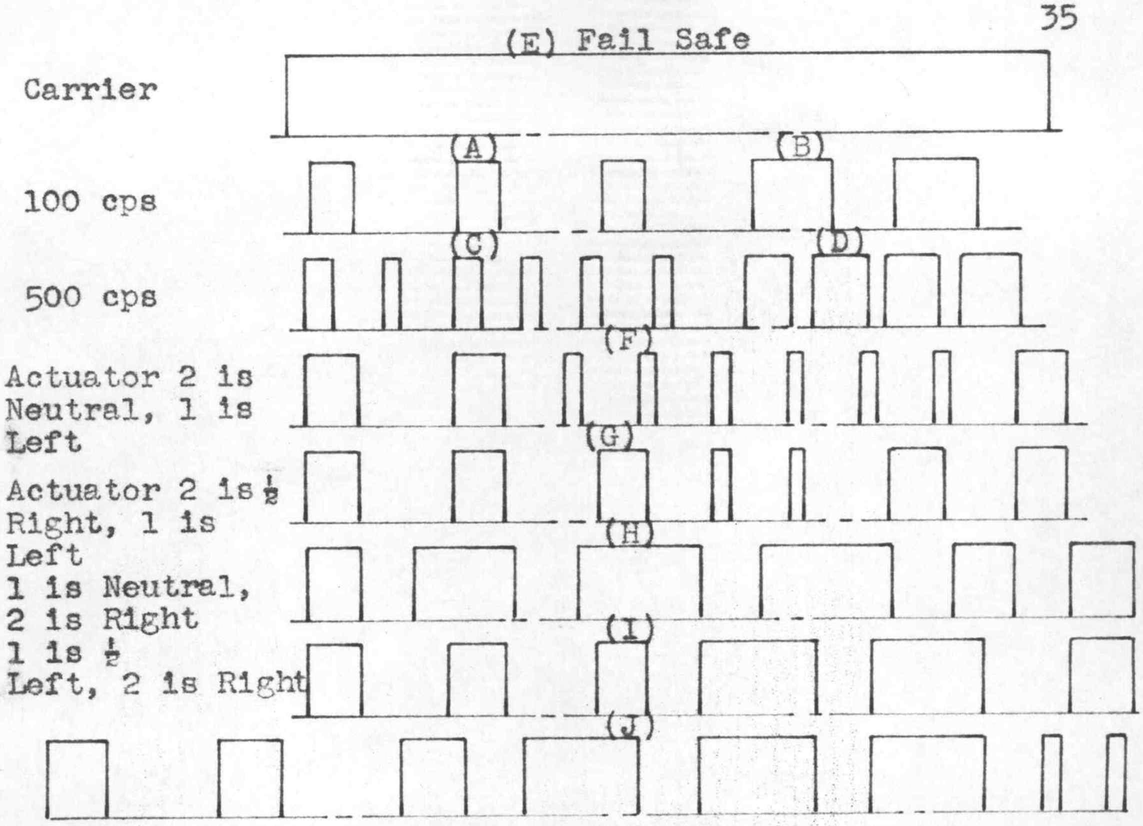


Figure 13

Rectified Square Wave Modulated Audio Signals, (7, Vol.47, p.21)

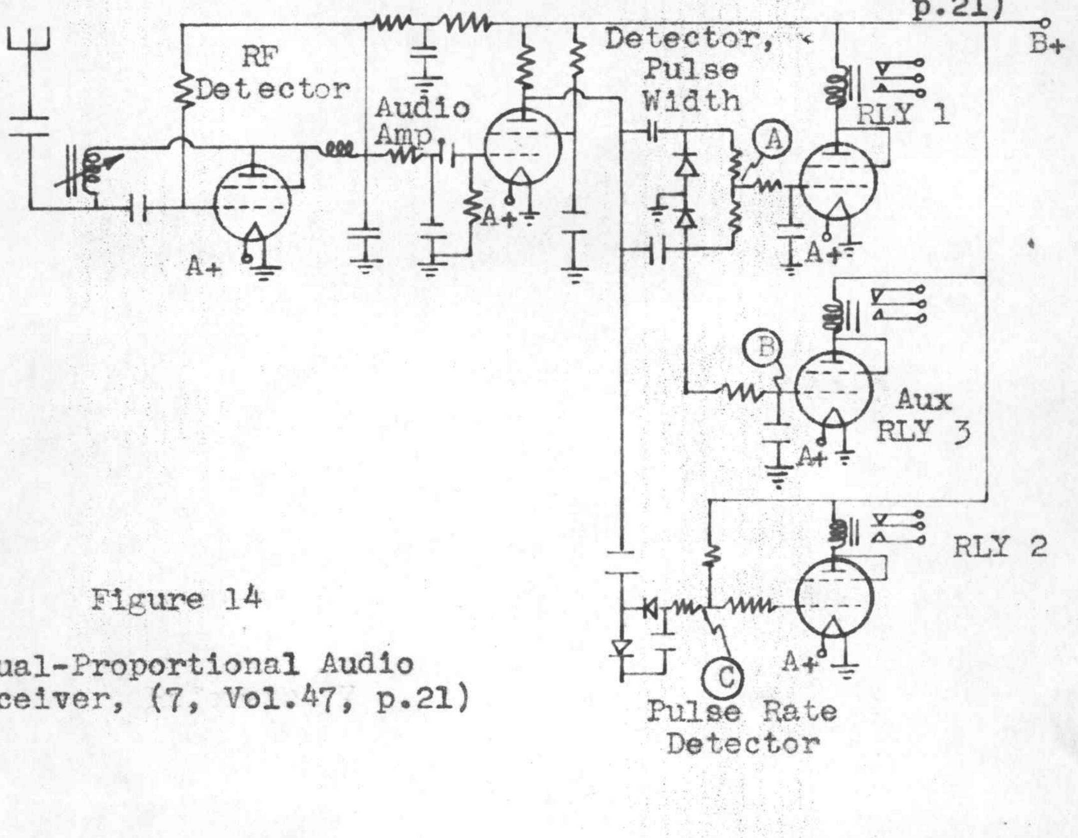


Figure 14

Dual-Proportional Audio Receiver, (7, Vol.47, p.21)

500 cps instead of 100 cps. This does not disturb the pulse width detector; however, if the transmitter is switched from 100 to 500 cps with varying dwell time, there will be another pulse circuit operating simultaneously with the first, Figure 13-J. A circuit is now required which will be insensitive to the pulse width for this operation; the pulse rate detector in the lower right of Figure 14 does this. It delivers a negative voltage at "c" for high tones and little, or zero, voltage for low tones.

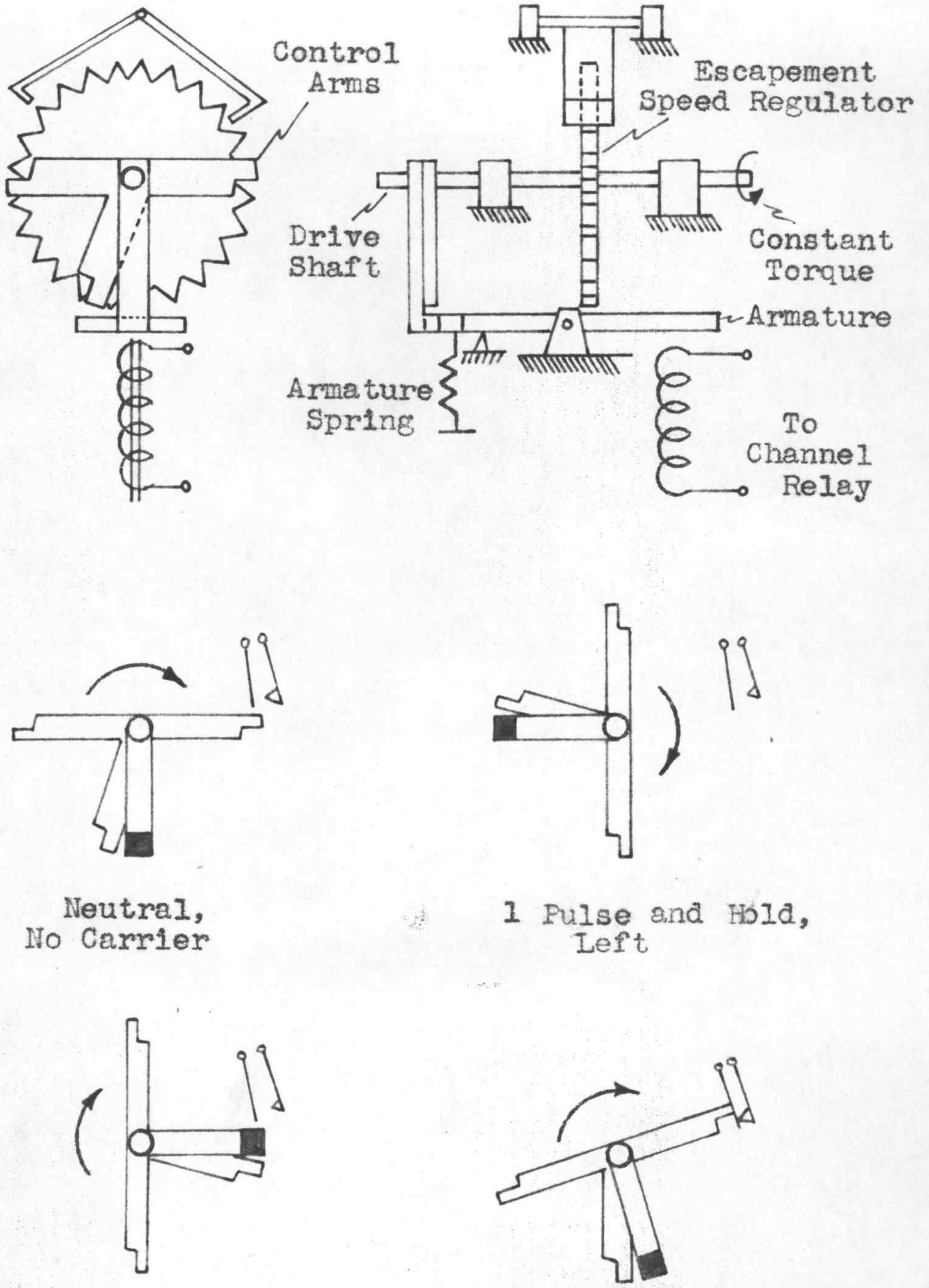
While the rate and width relays are operating, there is always tone present. When the third relay tube is connected into the negative end of the pulse width bridge as shown, its relay will remain open as long as tone is received. By connecting a simple numerical sequence actuator into the normally open contacts, its operation may be obtained by momentary interruptions of the tone or carrier. Further, by connecting the power supply for the servo system through the normally closed contacts, fail-safe operation is obtained. Power is removed, returning the system to neutral, upon failure or erratic operation. The system becomes reoperative upon resumption of normal conditions.

The advantages, disadvantages, and uses are the same for this system as with the previously described pulse width and pulse rate systems. However, this method does allow the use of damped actuators and an additional channel. Three channels is still short of the required minimum of ten, however. Specifications will be found in the Receiver System Specifications of the Appendix.

Compounded Escapements

Compound escapements are numerical sequence decoders of very light weight. While numerical sequence detectors have already been briefly mentioned in chapter two, these particular types are very popular and are combined, or multiplexed with other systems. Figure 15 shows a typical five arm escapement. Torque is supplied to the pawls, or arms, via the shaft passing through the escapement arms. As long as the coil is not energized, as shown.

The two possible control positions and the auxiliary contact are shown on the bottom of Figure 15 with the necessary pulse sequences for the positions shown. For smooth action and reduced skipping, a clock-work type ratcheting unit is attached to the escapement shaft; this attachment slows down and governs the speed of rotation. It is possible to cascade these units. By connecting a comparable unit to the auxiliary contacts of the first (21,Vol.54,p.22-23). Thus the



Neutral,
No Carrier

1 Pulse and Hold,
Left

2 Pulses and Hold
Right

3 Pulses and Hold,
Semi-Neutral and
Auxiliary

Figure 15

Compound Escapement

second unit is operated by "pulse" units of three, while the first unit repeatedly cycles through to the second neutral, or auxiliary contact. For example, the third position on the second unit would require nine pulses in packets of three. The limitations of these units are the same as the numerical sequence units described in chapter four. In addition the operator must perform and remember the sequence himself. The units also cycle through the control positions before reaching the desired one. There may be as many as three such cycles and nine pulses for cascaded units. They are primarily intended for use where size and weight must be a minimum.

A typical installation, where a little more control is needed, might be a three channel bandpass audio receiver. Two of the channels are used normally while the third is connected to the compound escapement. The third tone will still give two control positions while providing an additional channel via the auxiliary contacts. This particular installation is very common and its specifications are shown in Receiver System Specifications of the Appendix.

Impulse Modulation

The previously discussed impulse modulation system offers several methods for increasing the available number of channels. The system described had one channel of audio and seven switching channels, all of which were simultaneous with maximum delay times of not more than 100 micro seconds. There are two methods of increasing the number of channels. First, a reed bank may be installed in the audio channel. This simple, light weight addition will give up to seven additional channels. Second, each of the other seven channels may be pulsed and all of the benefits of such systems will be obtained. These additions are beneficial and extensive, but they have not solved the original problem of complexity and weight. The weight is still the highest of all systems considered.

A Continuously Operating Sequence Selector

The method of employing a pulse presence and pulse absence decoder was presented under Pulse Codes in chapter two and was seen to have several advantages. The two strong points were its apparently simple operation and its vast number of possible control channels. A concession must now be made, however. While a given pulse arrangement does give a certain channel, it allows only that channel. Thus, $(n! + 1)$ channels are available but without simultaneous action, an important feature originally set down in the design criteria. Moreover, the system would require a set of single-pole-double-throw contacts at each position for each channel if the circuits are to be isolated as they must be. The result is that a four pulse system would have twenty five channels, but at the expense of one hundred single-pole-double-throw contacts. It is necessary, therefore, to reject this use of a pulse presence - absence system in favor of a new more practical solution allowing the desired simultaneous action.

A rotary selector or commutator is shown in Figure 16. This unit cycles through the twelve channel positions on each revolution of the arm and operates continuously. As the arm passes over each channel position, the desired channel will be activated by a pulse at that instant; the lack of a pulse will leave the channel inoperative. If the channel relay is connected so that once closed it will remain closed, control of the desired channel can be had even after the pick-up arm leaves the channel position. The relay will remain closed, however, and there must be some method of releasing it when control is no longer desired.

Placing a normally-closed switch in the relay holding circuit will complete the system. This switch must be positioned so that its operation occurs just before the contact arm again reaches that particular channel position. Now any or all channels may be selected at will. Each will receive its individual

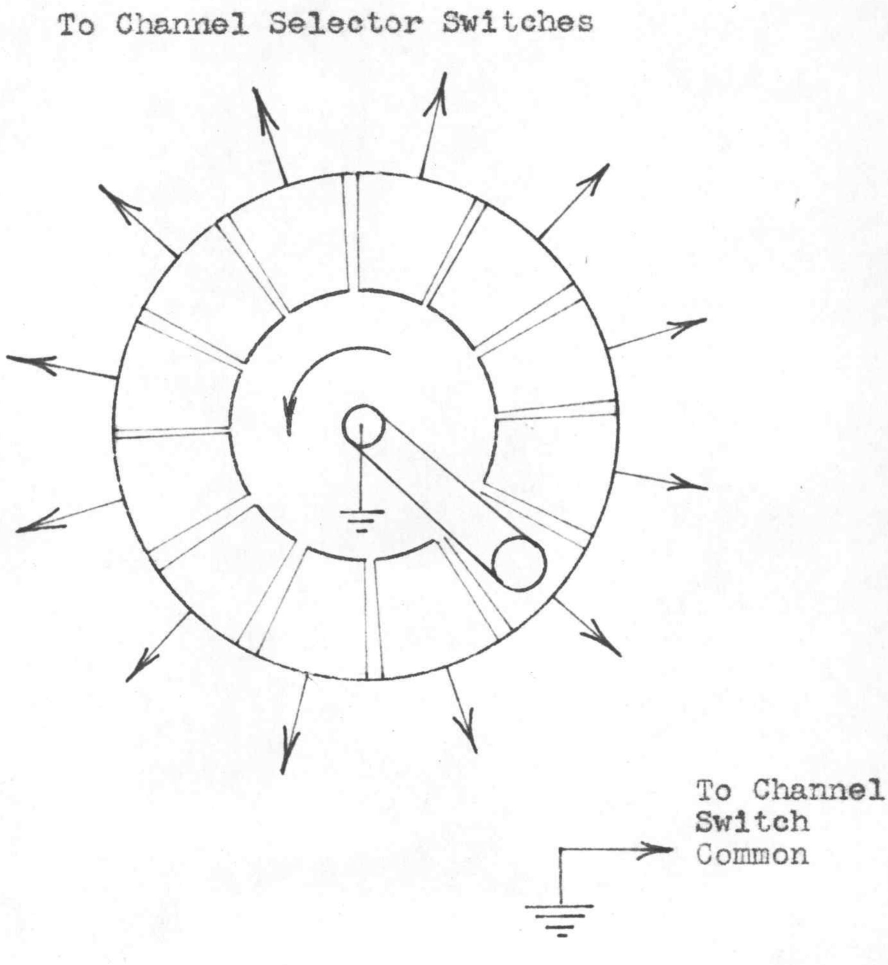


Figure 16

Rotory Channel Selector

commands, either on or off, for every revolution of the selector contact arm. There are still limitations in this system; however, the seriousness of these shortcomings must be evaluated only after study and development brings out their limits.

This new design appears to be the most promising thus far. It satisfies the important requirements of simultaneous operation and number of channels. In this respect it is superior to the others, excepting the prohibitively complex and heavy impulse modulation systems. The entire decoding and coding units are independent of the receiver and transmitter employed. They operate separately and there appears to be no reason why any simple receiver and transmitter would not work. Thus, it would seem that use could be made of certain equipment already available. How well it meets the other requirements will depend upon design problems encountered and the actual components used in the system itself. This will be covered in the following chapters.

CHAPTER 6

THE CONTINUOUS SEQUENCE SELECTOR UNITS

Decoder

The foregoing chapter has explained how the desired decoder will work and hardware must be designed to accomplish these results. Figure 17 shows the schematic diagram for the decoder circuit. Since the transmitter and receiver units must be synchronized, one channel position is employed for this purpose, leaving eleven useful ones. There are several methods of separating the synchronous signal from the normal ones; however, the most direct and foolproof method is to use a two channel transmitter and receiver. Such a receiver is the Babcock BCR - 7. It is a 465 MC bandpass unit and was chosen for its lightweight, rugged construction, simultaneous operation, and high pulsing speed. There are several other two channel units available which are also satisfactory.

For the unit described, with two double-pole-single-throw relays, there are three possibilities - closing relay number one, closing relay number two, and closing relays number one and two. Relay number two will be used to pulse the selector, relay number one will be used for synchronization, and closing relays number one and two will be used for channel selection.

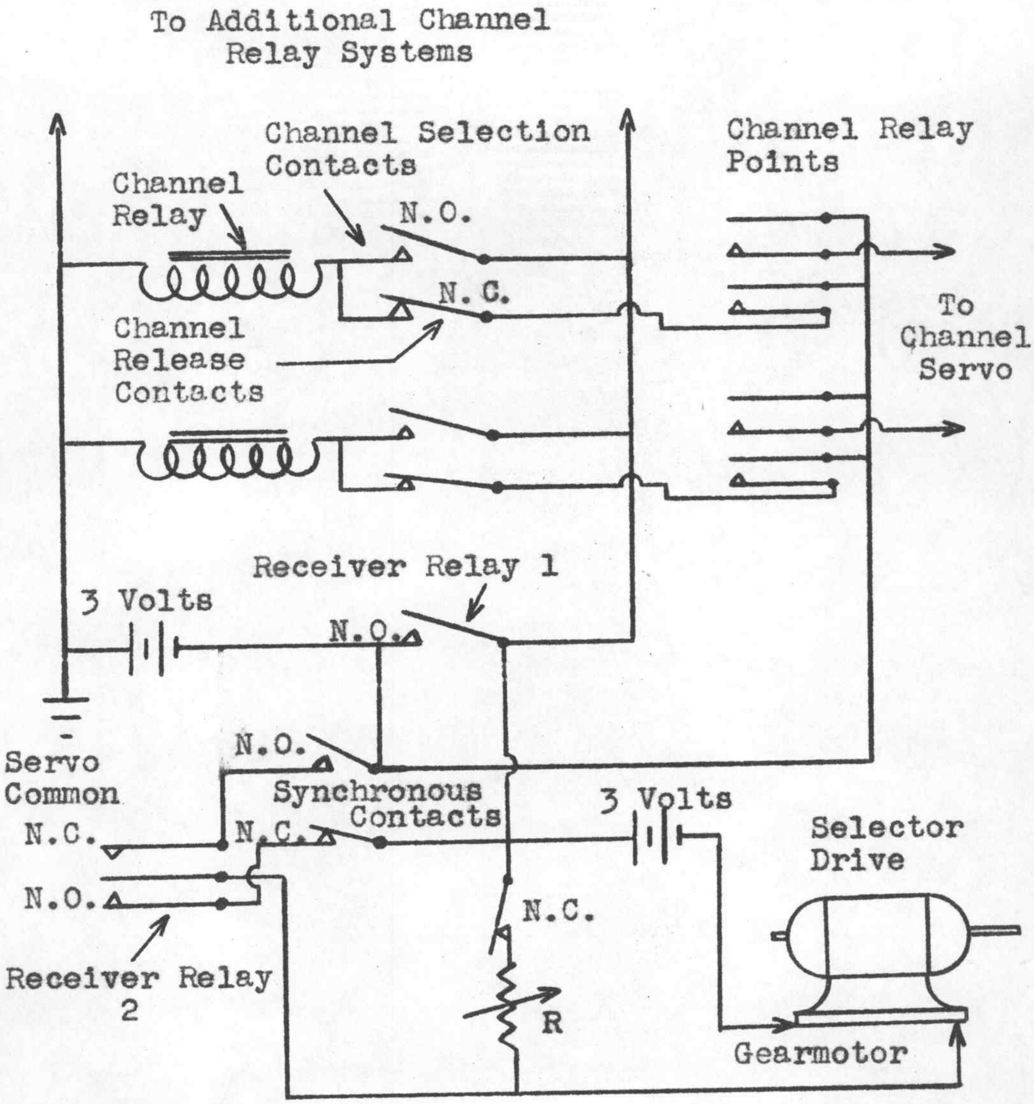


Figure 17

Continuously Operating Numerical
Decoding Circuitry

When the decoder rotates to the synchronous position, it operates the two synchronous switches indicated in Figure 17. The normally-closed contact removes receiver relay number two and places relay number one into this circuit. Since the selector drive motor circuit also passes through the normally-closed contact of receiver relay number two, the selector must remain at the synchronous position, until the transmitter unit also reaches its synchronous point. At this moment the transmitter will operate relay number one only, and the two units will step off in synchronization and normal operation. Note that realy number one will operate singularly only at the synchronous position.

The selector drive employs a small D. C. gear-motor placed in the circuit of Figure 17 as shown. The drive motor gear train has a drag brake which is constantly engaged and which causes rapid deceleration of the system whenever power is removed. Power is delivered to the motor via two circuits, excluding the synchronous position. First, the motor is pulsed by relay number two, and this pulse will arrive while the selector is positioned on a normally-open channel location. This momentary pulse is not sufficent to sustain rotation of the selector to the next position.

The normally-open contact of the motor circuit is now closed by a twelve lobe cam mounted coaxially with the channel selector, thus continuing the flow of current to the drive motor between selector pulses. When the motor reaches the synchronous position it will either pass smoothly through or be dragged down by the brake, according to the presence or absence of a pulse. Thus, by adjusting the drive motor speed with R to a rate just slightly above that of the ground unit, it will always be held to synchronous speed but will not lag behind. Bypassing R in the synchronizing circuit, as shown in Figure 17, will deliver full battery voltage to the motor during the synchronizing pulse and help to overcome any loss in momentum if it should be at rest due to nonsynchronization during the previous revolution.

Channel selection is accomplished with a single-lobe cam and a single-pole-single-throw normally - open contact, one for each channel, is placed on a cylinder at intervals of 30°. The synchronous contacts, which are a stacked pair, occupy the twelfth segment. One is the single-pole-single-throw normally - closed and the other is the single-pole-single-throw normally -open. Adjacent to the selection contacts are the channel - release contacts; these contacts are momentarily opened as the cam lobe passes to the corresponding channel selection points. Figure 17 shows how the channel points are connected to their respective double-pole-double-throw channel relays.

When the cam lobe closes a given normally-open contact, that channel relay can be activated via relay number one. Note that while all relays are connected to the same common battery, they cannot all be simultaneuosly energized by relay number one as the normally-open contact is the last link in the chain. Only one channel relay can be closed at a time by the single lobe cam. A pulse from relays number one and two will now pull in the channel relay and step the selector on to the next position.

Once the relay is closed, one set of the relay contacts are used to hold it in by connecting the battery through the normally-closed contacts. Thus the channel relay will hold itself closed until the selector cam again returns to this position. When the selector cam again reaches this point the normally-closed contact is opened, releasing the relay, and the normally-open contact immediately closes, readying the relay for continuation or cessation of control.

The relays employed are one hundred ohm, three volt units weighing one half ounce each and were developed for radio control applications by Jaico Products. Channel servos are connected through the second set of relay contacts and use the relay power supply thus reducing the battery requirements for those cases where the servo voltage needs are the same as for the selector drive motor and channel relays.

Coder

The coder is mechanically very much like the decoding selector. Figure 18 shows the coder circuitry. The same type drive motor, cam, and mechanical layout are used with some modifications. First, there are no normally-closed contacts, as they are unnecessary, and there are twelve normally-closed contacts arranged at 30° intervals as before. All twelve are individually connected through their respective control switches on the control panel; from there they are connected in parallel across the number one audio frequency keying line. The synchronous position is connected directly across its contact, since it must be transmitted on every revolution. Thus, at each channel position the respective channel switch will govern the emission of audio frequency number one and the subsequent closing of the channel relay at the receiver end.

The selector drive-motor cam in the decoder is now modified by the removal of the lobe corresponding to the synchronous location. A normally-open contact is placed over the cam and connected to audio frequency

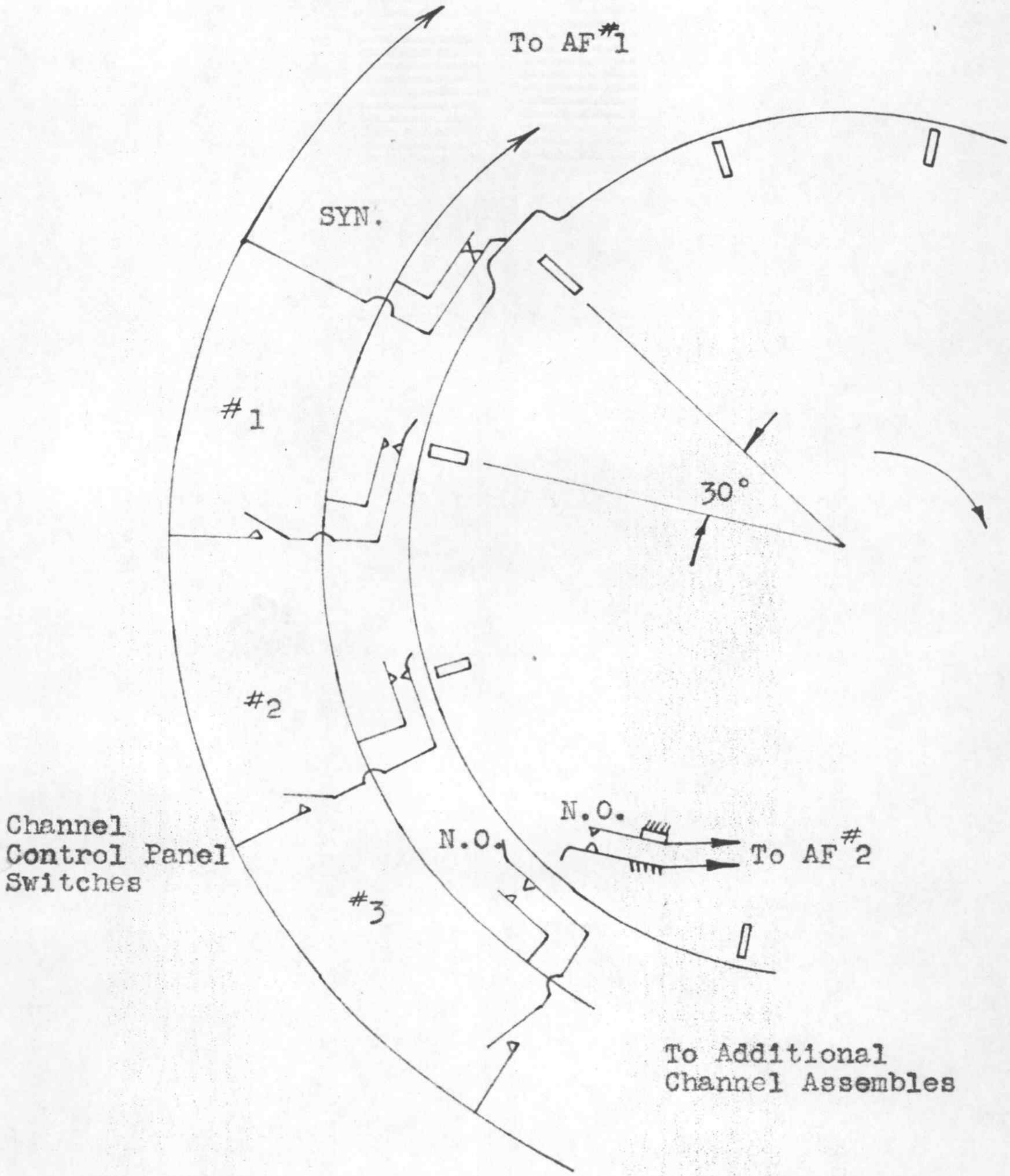


Figure 18

Coding Circuit

switch number two. The contact is adjusted so that it closes as the normally-open channel selector contacts close. It must also be positioned over the missing lobe while the selector cam is operating the synchronous contact. Thus, audio frequency number two pulses are transmitted simultaneously with pulses from number one, when selected. At the synchronous position only audio frequency number one can be sent. All that is necessary to complete the coding circuit is to install the variable resistor in the motor circuit for speed adjustment, and connect the unit into the transmitter keying lines.

Photographs of the assembled equipment, as described, will be found in the Exhibits.

CHAPTER 7

OPERATIONAL PROBLEMS AND DESIGN MODIFICATIONS

Coding Unit

In April of 1956 the first such system, an eleven channel unit, was designed and a test model was constructed to ascertain the feasibility of the original proposal. The results were gratifying, in that the proposed system proved workable. As this was a test unit, there was still the problem of a subsequent working model which would have to perform at higher rotational speeds and meet the design criteria of weight, size, ruggedness, and dependability.

The first prototype, an eleven channel unit, was completed in September of 1957. Operation is on 465 MC and the total weight of the complete control system, including servos and batteries, is sixty-three ounces.

In its final form the selector system is a small, eleven-channel unit weighing approximately twelve ounces. Both the coder and decoder units are such that they can be attached to most dual-channel transmitters and receivers, with little or no modifications, thus converting them to eleven channel operation. This adaptability should increase the systems flexibility and usefulness, particularly on the active citizens' bands.

The coding unit is connected directly into the audio section of the transmitter. Further, the method of keying the transmitter has been slightly changed. The manufacturer intended for two individual double-pole-double-throw switches to be used with the transmitter, while the coder is wired in as two single-pole-single-throw switches with one side of the switches in common. This does not seem to have any serious detrimental effect; yet, the multitude of coder contacts, the long keying leads, and the direct pulsing of the audio tones by the coder contacts lead to considerable electrical noise. It was also found that the speed of the drive motor was rather erratic, and this disturbed the performance markedly. This will be covered more thoroughly in connection with the decoder.

Several important changes are required in the coding unit for improved performance. First, the drive motor must be changed as the unit used was of poor construction and did not have suitable speed regulation. It would occasionally stop altogether, an intolerable condition. Reducing friction and interference to the cam action and its shaft is also in order; this will ease the drive motor problem as well. Second, it is possible to all but eliminate the noise problem by shielding the entire coder and using six volt remote relays to operate the transmitter. These relays may be mounted next to their respective audio sections in the transmitter itself, and by using double-pole-double-throw contacts the transmitter may be restored to its intended method of operation. It was also discovered that double-pole-double-throw keying would allow an increase in the allowable pulse rate from twelve cps to twenty-six cps, which is the maximum as specified by the manufacturer. Since this effectively cuts the control lag to less than one-half second, a substantial gain is made. Figure 1 of the Appendix shows the redesigned decoder. Both coding and decoding units are mechanically identical.

Decoding Unit

Perhaps the most difficult problem with the entire system is synchronization, and the coder and decoder must be synchronized. The same problem exists here as with the coder, i.e. the drive motor. The drive motor speed must be constant; this it was not. This problem was aggravated further by the erratic operation of its counter part on the transmitting end. Even so, the units would function very well for initial periods of about three minutes. After this time the decoder would begin to lag behind the coder and the motor drag brake would stop the motor on the synchronous position. The decoder would step off of the synchronous position on every other revolution until its speed again was equal to or slightly greater than that of the coder. It would usually be some time before normal synchronism would be obtained. No amount of adjustment would compensate or correct for this erratic operation. Moreover, as the motors were used they became more and more erratic until operation ceased. The normal operating period was reduced from three minutes to zero. With the coder changes mentioned previously, there is a steady, reliable signal coming in, and a large part of the problem is already solved.

At this point the decoder drive motor is replaced with a twelve-arm escapement unit as shown on the redesigned decoder in the Appendix. The only change of circuitry in the decoder is the elimination of the drive motor cam and its normally-closed contact. There is no reason to doubt the operation of the escapement as the original prototype had just such a unit and functioned without fault. Such a unit is insensitive to variations in coder pulse rate and eliminates this operating difficulty completely. A gear motor drive was proposed for its smoother, continuous action. However, in the interest of reliability and stable operation the escapement's advantage is its ability to index very rapidly to the next position where it awaits another pulse.

All the contacts used in the decoder are of the open-leaf type and are mounted on the outside. They are well exposed for adjustment, which is frequent since they are too easily disturbed. There is no difficulty in their operation; however, they leave much to be desired from a size and reliability stand point.

First, the contacts are replaced with very small snap-action micro switches mounted around the cylinder in same manner with their actuating buttons protruding through drilled holes into the inside of the cylinder, as shown in Figure 1 of the Appendix. The switches are adjusted so the actuating buttons will protrude through to the inside of the cylinder, the amount of the button protruding being the stroke necessary to make good contact. Now, the selector cam is replaced with an arm and a spring-loaded roller. This method will give smooth, positive contact action and will enclose the contacts, making adjustments a one-time operation.

Receiver

Receiver problems were minor. The receiver did follow the fast pulsing except for a troublesome, sticking relay which caused some trouble. These relays are hermetically sealed and cannot be adjusted; the manufacturer realized this shortcoming and all units of recent manufacture come with smaller, open, adjustable-contact relays.

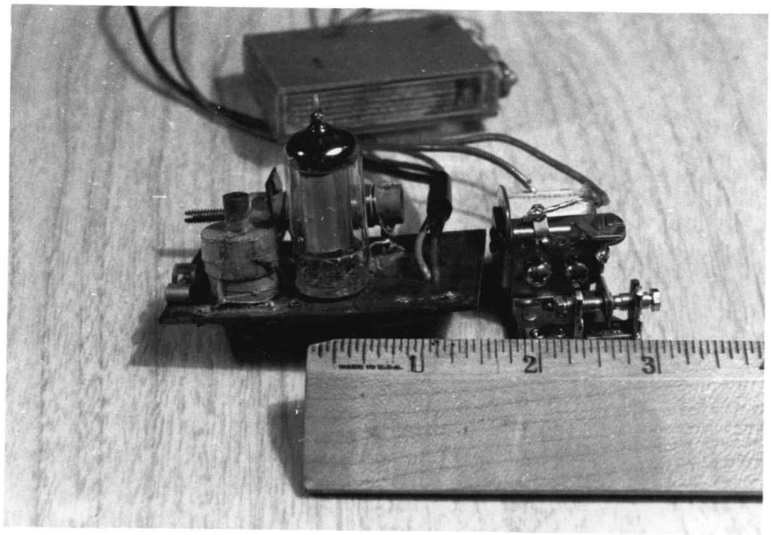
The only other change that might be mentioned is the replacement of the channel relays. The relays used functioned without difficulty; however, at one-half ounce each there are five and one-half ounces in relay weight alone. The relays are mounted separately in a plastic case, as shown in the Exhibits. By using smaller relays, it is possible to mount the decoder, receiver, and relays on one chassis rather than separately as before. The replacement relays weigh 0.09 ounces each for a total weight saving of 3.28 ounces, but at an expense of five times that of the originals. The replacements are desirable but expensive, and in some cases may be justified. Since low cost is one of the objectives, however, they are not felt to be desirable at least at this time.

The redesigned system has its specifications listed with the others in Table of the Appendix. Specifications are also given on the system before redesign but with improved selector drive motors being employed. The features of this redesigned system are enumerated below:

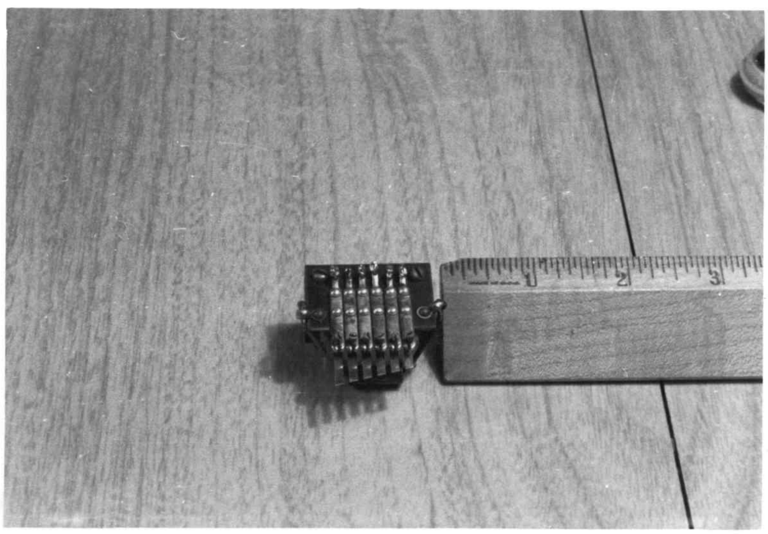
1. Single frequency operation.
2. Interference rejection as good as the receiver employed, and stray, disturbing signals cause erratic operation for no more than one-half second, the time for one revolution of the decoder.
3. Reliability of a high order, no individual components of an unusual nature or operating under abnormal conditions.
4. Simple operation. Alignment permanent after the initial set up adjustments.
5. Size and weight a minimum considering the number of channels.
6. Ruggedness.
7. Number of channels desired a question of tolerable control lag rather than any channel number limitation.
8. Simultaneous operation.
9. Control lag of one-half second for the eleven channel system.
10. Retail cost favorable with other systems of five or more channels.
11. Adaptability. Coder and decoder attachable to any two-channel receiver for eleven channel operation.

Considering these features and comparing its specifications with other systems in the Receiver System Specifications Table of the Appendix. It is felt that this system satisfies more completely the requirements of:

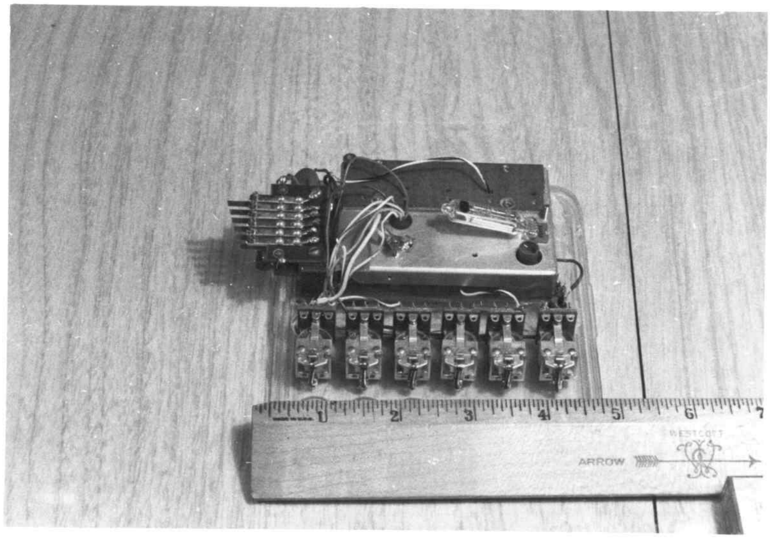
1. A competitive price.
2. Light weight.
3. Single radio frequency operation.
4. Interference resistance.
5. Ruggedness.
6. Ease of operation.
7. Small Size.
8. Ten or more channels.



Single Channel Receiver



Reed Bank



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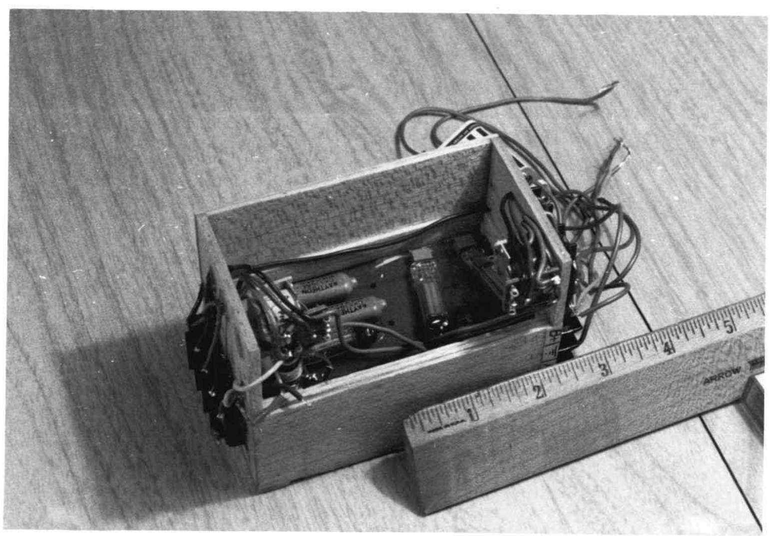
Six Channel Reed Receiver



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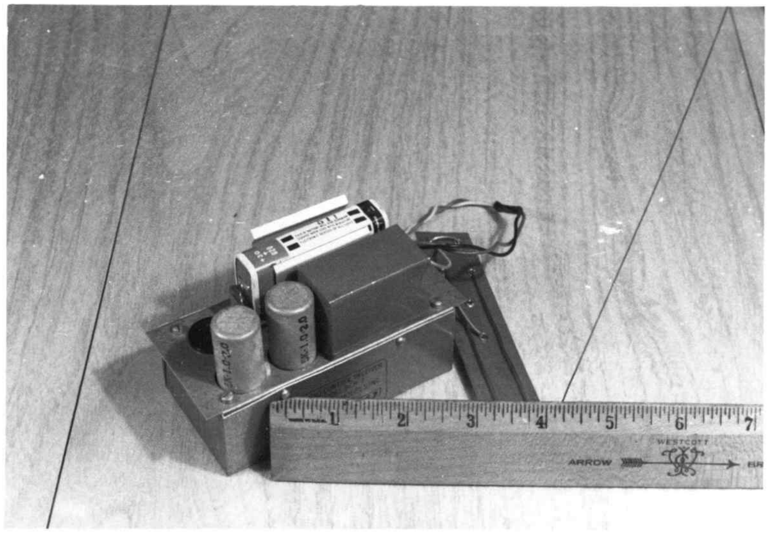
Two Channel Bandpass Receiver



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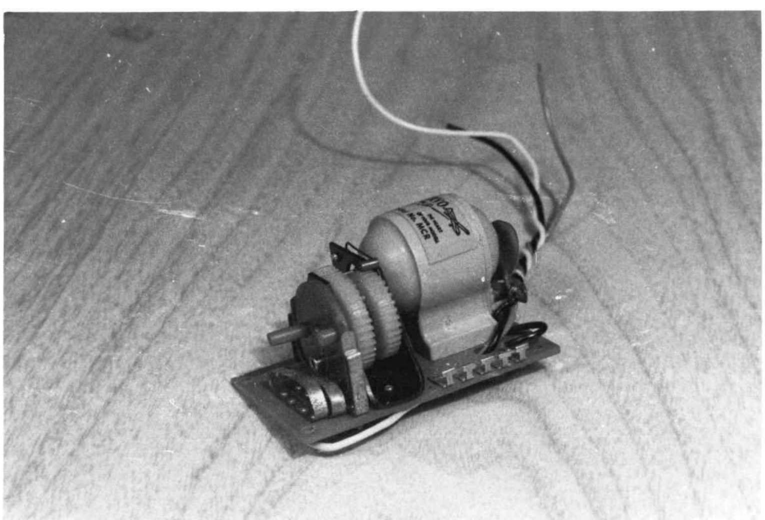
465 MC Two Channel Receiver



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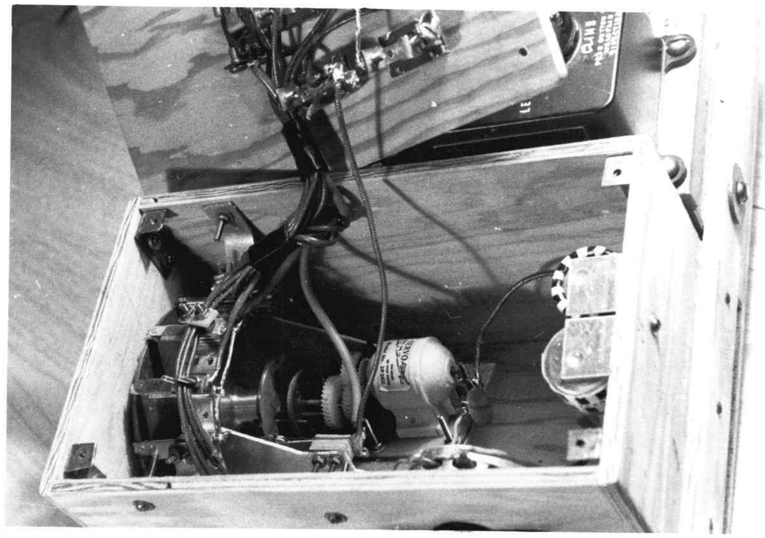
Selector Drive Gearmotor



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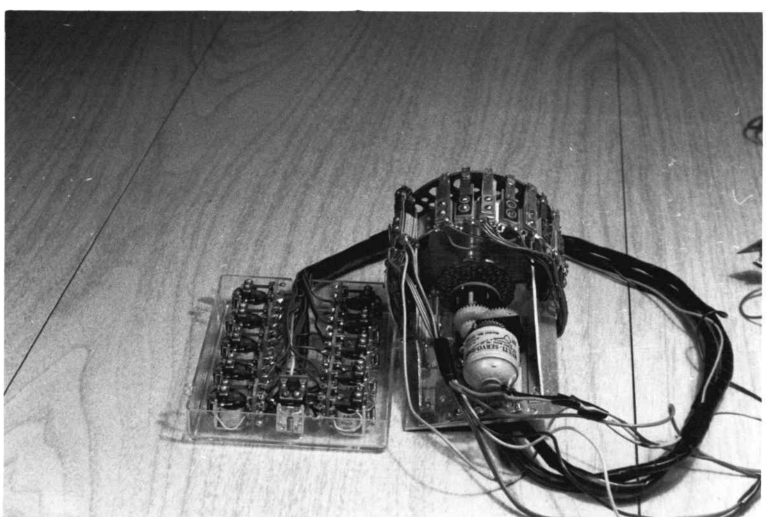
Coder



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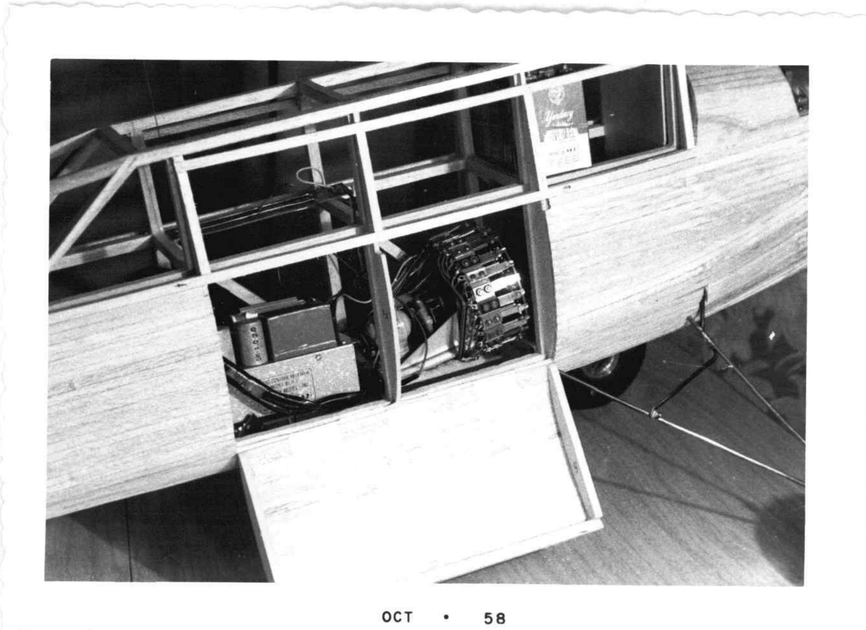
Decoding Selector and Relay Bank

Coder and Control Panel
Mounted on the 465 MC Transmitter



Receiver System Mounted in Drone
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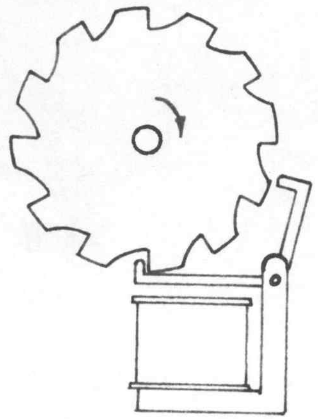
APPENDIX

Receiver System Specifications									
Receiver System	List Price (2)	Channels	Weight(4)	Simult.	approx. Lag	Proportional	Volume (3)	Xmiter Weight	Power Consumption
Constantly operating pulse selector, Final design	$215 (1)	11	23 oz	Yes	1/2 sec.	No	10 in³	9.78 lb	2 Watt(1)
Constant pulse selector, first design	213 (1)	11	33.85	Yes	1 sec	No	91 in³	9.78 lb	1.92
Reed receiver	239	8	9	Any 2	1/3 Sec.	NO	16.9 in³	4 lbs	0.27
Audio band pass receiver	155	3	5.3	No	0	No	23.5 in³	4 lbs	0.81
Numerical sequence receiver	135 (1)	10	34	No	2 sec	No	90 in³	10	2
Impulse Width	120	6	12	No	1 Sec	No	25 in³	4	1.83
Impulse Width and rate	148	12	21	Any 2	1 sec	No	47 in³	4.5	3.51
Impulse Modulation	500	8	61.6	Yes	0	Yes	225 in³	10	29.98
Two tone pulse width	165	2	7	Yes	0	Yes	19 in³	5	0.75
Compound Escapement, Use with any receiver	9	1 Additional	1/2	NO	1/2 (1)	No	5 in³	—	1.125

Notes: (1) = estimated (2) Includes xmiter (3) Smallest Containing prism (4) Less Battery

Redesigned Channel Selector

Escapement detail



Notes:

1. Frame is of cast Mg alloy.
2. Escapement parts are hardened Steel.
3. Drum is machined concentrically With the ball mounted main Shaft.
4. Scale = full