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16. Abstract

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SUMMARY

The Langley Research Center uses radio-controlled, scaled aircraft models to study the spin-entry characteristics of aircraft. Recent spin-entry studies required the use of an electronic proportional-control system for manipulating model control surfaces. In order to meet control system requirements, a special-purpose analog computer was designed to simulate the coupling between roll and pitch controls. A digital encoder was designed to encode the voltage analogs of control-surface position into a special pulse format for transmission to the model. This report describes these two special developments and their relationship to the functions of the overall control system.

INTRODUCTION

The study of the dynamic characteristics of aircraft when controlled flight begins to diverge into uncontrolled spin has been difficult to perform accurately in wind tunnels and too expensive and dangerous to perform on piloted aircraft. In order to study this transition region, unpowered scaled models of aircraft are released from an aircraft and guided from the ground by radio control into the potentially unstable flight conditions which lead to uncontrolled spin.

The model pilot is located on the ground and controls the aircraft model by using a control stick and foot pedals while watching the model through binoculars. The pilot's controls are attached to potentiometers which convert the control position into electrical signals. These electrical signals, representing the commands of the pilot, must be accurately transformed into control-surface deflections for the scaled model in such a way that the model flies with the aerodynamic characteristics of the full-scale aircraft. The ground electronics system transforms the pilot commands into control-surface-position signals. These are transmitted to the model where the airborne electromechanical system transforms the control-surface-position signals into the mechanical deflections required of the control surfaces.

This control system is a proportional-control system in that the control-surface movement is proportional to the displacement of a control stick. It replaces a bang-bang control system in which control was achieved by always moving the control surfaces full travel for any control input.

This report discusses the ground portion of the radio control system and how it performs the electronic transformations which result in the encoded signals transmitted to the model. Mechanical limitations of the aircraft control surfaces and automatic spin-prevention techniques for the aircraft are electrically simulated within the radio control system.

SYMBOLS

l_C	slope of climb limit curve
l_D	slope of dive limit curve
m	roll to differential stabilator scale factor
n	pitch to collective stabilator scale factor
t	time
t_1	Channel 1 data pulse
V_D	differential stabilator control voltage
V_{HL}	left stabilator control voltage
V_{HR}	right stabilator control voltage
V_K	full-scale voltage for control voltages
V_L^+	positive voltage limit for V_D
V_L^-	negative voltage limit for V_D
V_P	pitch-stick position voltage analog
V_{PC}	voltage at which limiting action occurs for climb
V_{PD}	voltage at which limiting action occurs for dive

V_R	roll-stick position voltage analog
δ_D	differential stabilator angular displacement
δ_{DL}	limited value of δ_D
δ_H	collective stabilator angular displacement
δ_{HL}	left stabilator angular displacement
δ_{HR}	right stabilator angular displacement

Subscripts:

max	maximum
min	minimum

MODEL CONTROL REQUIREMENTS

A typical model will require control of ailerons, rudder, and horizontal-tail surfaces. Control of the horizontal-tail surfaces of the models affords a convenient example for discussion of the simulation of mechanical controls. Many of the scaled aircraft models have split horizontal stabilators which move collectively (together) to control pitch and differentially (in opposite directions) to aid roll. The pitch and roll commands which actuate these surfaces come from different electrical and physical sources. The pitch command comes from the pitch-stick position and the roll command comes from the roll-stick position. The pitch and roll may be controlled by one pilot with a single two-axis stick through a gimbal arrangement or may be controlled by separate pilots. The roll and pitch are added and subtracted in a ground unit called the roll-pitch interconnect (RPI) to derive individual control voltages for the right and left sides, respectively, of the split horizontal stabilator. The derivation of stabilator control voltages is complicated by the limits placed on the travel of the stabilators. The limits are generated in the roll-pitch interconnect and are the simulation of the mechanical actuator stops which restrict stabilator movement on the full-scale aircraft.

The automatic spin-prevention systems are electronic in the full-scale aircraft and in the model. Generally, the pilot's control authority is reduced when he has flown the aircraft into a spin-imminent aerodynamic condition, such as a high angle of attack. The spin-prevention system removes enough control so that the pilot cannot fly the aircraft into a spin. The control surfaces affected by the spin-prevention system, the amount the surfaces are affected, and the aerodynamic conditions which trigger the system are different for each aircraft tested.

The aerodynamic conditions are measured by transducers located in the model and transmitted to the ground over a separate telemetry down-link. The spin-prevention system receives the information and activates the control surfaces in accordance with the spin-prevention scheme being implemented.

Since the ground electronics system must accommodate a wide variety of spin-prevention systems, an electronic interface point is provided where the spin researcher can insert his particular spin-prevention technique into the control law for the model. The encoder provides a linear transformation between the voltage at the interface point and the encoded signal transmitted to the model.

GROUND ELECTRONICS SYSTEM

The ground electronics for the control system are contained in two mobile units, as shown in figure 1. The model pilot operates the control sticks from the tracker trailer where, seated on a tracker mount, he watches the flight through binoculars. The pilot's control-stick position signals are transmitted over cables to the electronics van where they are buffered and amplified into standard analog-computer voltages. The buffered stick signals are fed through the roll-pitch interconnect or through an external spin-prevention system. The spin-prevention system can be an arbitrary function subject only to the constraints of interfacing with ±10-volt input and output voltages. It will, in general, include a roll-pitch interconnect as well as other nonlinear functions used to prevent spin. At the input to the encoder, the voltages no longer represent the pilot's stick position. The voltages represent the positions that the model control surfaces must assume in order to fulfill the control law. The control-surface-position signals are encoded and transmitted to the model. The two units described in this report are major elements of the system which were specially designed for this application.

STABILATOR ROLL-PITCH INTERCONNECT

Traditionally, the horizontal tail of aircraft consisted of a fixed portion called a stabilizer and small movable inserts called elevators. In modern high-performance aircraft, the entire horizontal tail moves and the word "stabilator" is often used to describe the surface.

The angular rotation of the right and left differential stabilators are denoted by δ_{HR} and δ_{HL}, respectively. Pitch trim of the aircraft is controlled by the collective or average position of these surfaces, that is, $\delta_H = (\delta_{HR} + \delta_{HL})/2$. Differential stabilator action, $\delta_D = \delta_{HR} - \delta_{HL}$, aids the ailerons in rolling the aircraft. In many instances, the value of δ_D is large enough for the commanded pitch and roll to cause a stabilator to reach its mechanical deflection limits (i.e., $(\delta_H + \delta_D/2)$ commanded $> \delta_{HR,max}$). When this happens, the maximum differential stabilator displacement is limited as a function of the collective action required by the pitch command. This limiting action can be described in the following equations written for the right stabilator:

$$\delta_{DL} = \delta_{D,max} \qquad \left(\delta_{HR,min} + \frac{\delta_{D,max}}{2} < \delta_H < \delta_{HR,max} - \frac{\delta_{D,max}}{2}\right)$$

$$\delta_{DL} = 2\left(\delta_{HR,max} - \delta_H\right) \qquad \left(\delta_H > \delta_{HR,max} - \frac{\delta_{D,max}}{2}\right)$$

$$\delta_{DL} = 2\left(\delta_{HR,min} - \delta_H\right) \qquad \left(\delta_H < \delta_{HR,min} + \frac{\delta_{D,max}}{2}\right)$$

The complete differential/collective limit is illustrated in figure 2 for a typical aircraft. The stabilator operates within the unshaded region according to the equations shown. Between the vertical dashed lines, δ_D may go to its maximum value and not conflict with the collective maximum displacement. Outside the dashed lines, δ_D must be limited to be no more than δ_{DL}. The vertical solid lines through $\delta_{H,max}$ and $\delta_{H,min}$ represent points where the commanded differential displacement plus collective displacement does not cause either stabilator to exceed a limit.

Figure 2 represents the excursion limits for differential stabilator movement. In order to simulate this limiting action in the control system, a voltage analog was constructed so that the control voltages to the differential stabilators were limited in the same manner as the mechanical actuators were limited on the real aircraft. The RPI computes voltage analogs of the quantities shown in figure 2. These voltage analogs are indicated in figure 3 and are defined by the following equations:

$$\left.\begin{array}{ll}
\left.\begin{array}{l} V_L^- = -V_K \\ V_L^+ = V_K \end{array}\right\} & \left(V_{PD} \leqq V_P \leqq V_{PC}\right) \\
\left.\begin{array}{l} V_L^+ = V_K - \ell_C \left(V_P - V_{PC}\right) \\ V_L^- = -\left[V_K - \ell_C \left(V_P - V_{PC}\right)\right] \end{array}\right\} & \left(V_P > V_{PC}\right) \\
\left.\begin{array}{l} V_L^+ = V_K + \ell_D \left(V_P - V_{PD}\right) \\ V_L^- = -\left[V_K + \ell_D \left(V_P - V_{PD}\right)\right] \end{array}\right\} & \left(V_P < V_{PD}\right)
\end{array}\right\} \qquad (1a)$$

$$\left.\begin{array}{ll}
V_D = V_R & \left(|V_R| \leqq |V_L|\right) \\
V_D = V_L^+ & \left(V_R > V_L^+\right) \\
V_D = V_L^- & \left(V_R < V_L^-\right)
\end{array}\right\} \qquad (1b)$$

$$\left.\begin{array}{l}
V_{HR} = nV_P + mV_D \\
V_{HL} = nV_P - mV_D
\end{array}\right\} \qquad (1c)$$

The input independent variables are V_P and V_R and the output dependent variables are V_{HR} and V_{HL}. The constants for the particular model tested are V_{PC}, V_{PD}, n, m, ℓ_C, and ℓ_D. These constants are preset on the RPI panel. The full-scale voltage for control voltages V_K is a system constant. The roll-pitch interconnect may be broken into three parts as shown in figure 4. Each part generates one of the groups of equations (1). The limit generator generates voltages representing the differential stabilator limits as a function of pitch-stick position as shown by the envelope of figure 3 and equations (1a). Two voltages are generated: one representing the right roll limit V_L^+ and the other representing the left roll limit V_L^-. These two voltages are compared in the differential limit switch with the voltage representing roll-stick position V_R. Based on the value of the three voltages, the logical decision described in equations (1b) determines the output of this block. If the roll-stick position voltage is larger than the roll-limit voltage (that is, $V_R > V_L^+$ or $V_R < V_L^-$), the simulated stabilator has exceeded the simulated mechanical limit. When this condition occurs, the output of the limiter is switched to the voltage corresponding to the amount of roll that would result in the maximum differential displacement obtainable by the full-scale aircraft (that is, $V_D = V_L^+$ or V_L^-). This voltage, and not the actual roll-command voltage, is used as the input to the adder/subtracter. If the roll-stick position voltage is less than the roll-limit voltage, then no simulated mechanical limit has been reached and the roll-command voltage is used in the adder/subtracter ($V_D = V_R$). The stabilator differential control voltage V_D thus limited is added and subtracted as shown in equations (1c) with the pitch-stick position voltage V_P (collective stabilator voltage) to produce right and left stabilator position commands V_{HR} and V_{HL}.

The roll-pitch interconnect is a special-purpose analog computer with the nonlinearities provided by reed relays. Relay activation time is fast compared with system response time and no appreciable error is introduced. Adjustments are provided so that a wide range of RPI configurations may be simulated.

Figure 5 shows a more detailed breakdown of figure 4. The blocks shown in figure 4 are identified at the bottom of figure 5.

The limit generator operates on the pitch-stick position voltage and contains separate limit generators for climb and dive. For example, when the pitch stick is in the climb position and its voltage exceeds the voltage breakpoint V_{PC} set by the climb-breakpoint potentiometer, the comparator activates the climb-limit relay. The climb limit is zero at relay contact closure since the climb breakpoint is summed with the equal in magnitude but opposite in sign pitch-stick position voltage V_P. As pitch-stick position voltage is increased, the climb limit becomes more negative. This negative voltage is summed with the positive maximum limit voltage V_K of 10 volts to result in a limit which begins at maximum limit for roll (that is, no limit on roll) and decreases linearly as a function of pitch-stick position voltage. The voltage analog of the "maximum right roll differential" V_L^+ is shown in figure 3. The right roll (positive) voltage limit V_L^+ is inverted to generate the left roll (negative) voltage limit V_L^-.

The differential limit switch detects with comparators when the roll-stick position voltage has exceeded its positive or negative voltage limit. When a limit is exceeded, the comparator activates a relay which replaces the roll command with the limit exceeded. For example, exceeding the left roll limit causes the left roll limit relay to close and the limit relay to switch to the limit position. The stabilator differential voltage output V_D thus is provided with the left roll limit.

The stabilator differential control voltage is summed with the pitch-stick position voltage in the adder/subtracter to give control signals for the left and right stabilators. These signals are encoded and sent to the model.

ENCODER

The encoder provides a linear transformation of the control-surface command inputs into a time-multiplexed stream of position-modulated pulses. Six channels are available for transmitting position commands to the model control surfaces. Typically, these channels are used for ailerons, rudder, left stabilator, right stabilator, and two spare channels. Each 0-to-20-volt input signal must be transformed into a pulse pair with a spacing of 0 to 1000 microseconds. Zero volts correspond to a 0-microsecond spacing and 20 volts correspond to a 1000-microsecond spacing. This format was selected for compatibility with an existing model control system.

The basis for the operation of the encoder is that both the 20-volt signal and the spacing of the pulses can be represented by the same range of numbers. Both the voltage and the pulse spacing are represented by the integers from 0 to 255. The voltage is encoded as 78 millivolts $\left(\frac{20 \text{ volts}}{256}\right)$ per integer step. Any input voltage between 0 and 78 millivolts is encoded as 0; any input voltage between 79 and 156 millivolts is encoded as 1; and so on. Any voltage in the range from 19.22 to 20.00 volts is encoded as 255. The spacing between pulse pairs is encoded as 3.9 $\left(\frac{1000 \text{ microseconds}}{256}\right)$ per integer step. Any spacing between 0 and 3.9 microseconds is encoded as 0; any spacing between 3.9 and 7.8 microseconds is encoded as 1. Any pulse spacing between 996.1 and 1000 microseconds is encoded as 255.

Once input voltage and pulse spacing have been encoded in a common basis, it is then possible to compare both quantities and decide what pulse spacing is to be generated for a given input voltage. For example, a 100-millivolt input voltage would be encoded as 1. The integer 1 corresponds to a pulse spacing between 3.9 and 7.8 microseconds and a pulse spacing somewhere within this time interval would be the generated pulse spacing.

In practice, the encoding process is implemented as shown in figure 6. The input voltage is first encoded into an integer between 0 and 255 by an 8-bit natural binary analog-to-digital converter and held for comparison. An 8-bit natural binary counter is then started from zero and the reference pulse is generated at the same time. The counter has a range from 0 to 255 and accumulates counts at the rate of 3.9 microseconds per count. A comparator monitors the encoded voltage and the output of the counter simultaneously. As time passes, the number in the counter grows until the comparator detects the same bit pattern in both the counter and the analog-to-digital converter. At this time, the numbers in the counter and in the analog-to-digital converter are equal and the second pulse of the pair is generated. The spacing between the two generated pulses is proportional to the input voltage since the length of time the counter counts is proportional to the encoded input voltage. This same process is repeated for each of the six channels.

As the encoder was actually mechanized, it does not use the exact numbers of the foregoing discussion, but in the following description the principle is the same.

The mechanized encoder transforms the analog voltages representing desired control-surface positions into a stream of position-modulated pulses in the form shown in figure 7. A frame length of 20 milliseconds is used to transmit all control-surface commands. Six time intervals in each frame, corresponding to six data channels, are shown in figure 7(a). A portion of a frame is shown expanded in figure 7(b). Each frame is started by a frame pulse. The frame pulse is distinguished by the long blank interval preceding it. One data pulse for each channel then follows. The data are encoded by the spacing (time delay) between a pulse and its predecessor. Zero is encoded by a delay of 940 microseconds and full-scale is encoded by a delay of 2065 microseconds. Only the first channel data pulse is referenced to the frame pulse. All other data pulses are referenced to the data pulse of the preceding channel.

Each channel may be broken into two time periods. The data select period is a fixed time of 940 microseconds. This period is used to select and digitize the analog voltage to be encoded by that channel. The data encode period is a variable time which varies from 0 to 1125 microseconds in proportion to the data to be transmitted. Zero time corresponds to a -10-volt analog input signal and 1125 microseconds correspond to a +10-volt analog signal. Each channel pulse spacing may range between 940 and 2065 microseconds, depending on input voltage. When the pulse for the last channel is transmitted, the encoder stops until the next frame pulse appears.

In normal operation, the encoder-buffer amplifiers deliver a +9-volt full-scale signal to the encoder. In this case, the encoded delay varies from 1000 to 2000 microseconds. The extra range is available as a front panel adjustment to compensate for drifts in the model electronics.

Figure 8 is a detailed timing diagram for the encoder and figure 9 is the detailed block diagram. Figure 8 shows the first channel timing and part of the second channel timing in relation to the advancing count in the data counter. During the fixed period of 940 microseconds, the data counter advances from a preset value of 42 ($t = 0$) to a value of 255 ($t = 940\mu sec$) in one-count steps at the rate of 4.4 microseconds per step. At preprogramed counts, corresponding to particular time values, operations such as analog-to-digital conversions are caused to occur. At $t = 940$ microseconds, the variable period begins. This period depends on the data and may be anywhere from 0 to 1125 microseconds.

Overall operation of the encoder may best be understood by relating the block diagram of figure 9 to the timing diagram of figure 8. Inputs to the encoder are the ±10-volt analog signals. The output is the pulse sequence of figure 7. A crystal oscillator drives the data counter and the frame pulse generator. The frame pulse starts each frame by setting the On/Off control to "On," which establishes initial conditions on the data counter, presets the channel counter to an initial count, and activates the signal conditioning to send out the frame pulse. The data counter advances in 4.4-microsecond increments from the initial condition of $t = 0$. At $t = 378$ microseconds, the programer generates a channel advance pulse. This pulse advances the channel counter one count. The count in the channel counter is the address used by the multiplex (MPX) to connect one of the six channels to the 8-bit natural binary analog-to-digital converter (ADC). At $t = 519$ microseconds, the programer generates the digitize command pulse for the ADC. Within 18 microseconds, the selected channel is digitized and the digital data are applied to the input of the data store. A signal of -10 volts is digitized as 0 (all 0's in the 8-bit binary word) and a signal of +10 volts is digitized as 255 (all 1's in the 8-bit binary word). At $t = 659$ microseconds, the programer generates the transfer pulse which loads the digitized data into the data store. At 940 microseconds, the data encode period is enabled by the programer. During this period, the eight least significant bits of the data counter are compared by the comparator with the data stored in the data store. The eight least significant bits of the counter are all 0 at $t = 940$ microseconds. The counter advances 4.4 microseconds per count as it counts in natural binary. When the number in the counter is equal to the number in the data store, a data pulse is generated. As the number in the data store is made larger (representing a more positive analog voltage), the counter takes longer, by 4.4 microseconds per count, to reach a comparison. The -10 volt signal is digitized as 0 and the comparison is made at $t = 940$ microseconds. The +10-volt signal is digitized as 255 and the comparison is made at $t = 2065$ microseconds. In this way, the data pulse for each channel is generated between 940 and 2065 microseconds after the reference pulse, depending on the value of the analog input voltage to the channel.

The data pulse generated for channel 1 serves as the reference pulse for channel 2. The channel 2 data pulse is generated in the same manner as the channel 1 data pulse. The process continues until the last channel has been encoded. When the channel decode detects that the channel succeeding the last valid channel has been reached, it allows the reset pulse to propagate through and turn the On/Off control to "Off." The reset pulse occurs at $t = 237$ microseconds for each channel. The data counter is stopped until the next frame pulse begins a new frame.

RESULTS

Both the encoder and the roll-pitch interconnect were fabricated on printed circuit boards and installed in the ground electronics system. The ground electronics system has been used with three stall-spin research models and has been operational for over 1 year. During that time, the two circuits have been accurate, stable, and free of failures.

Four additional simplified systems have been produced for laboratory use with similar results.

CONCLUDING REMARKS

A flexible ground electronics system has been designed for use in the spin-entry study model program and has established an interface where spin researchers can conveniently simulate the characteristics of existing or proposed aircraft control systems. The spin-entry study models are free-flight scaled models which are released from an aircraft and flown from the ground by radio control. The ground electronics system provides the transformation of pilot signals into control-surface-position signals before transmission to the model. A special-purpose analog computer was developed to simulate the nonlinear control functions which are required by many models. The digital encoder has provided a linear, voltage-to-time conversion which permits insertion of special model control functions. The ground electronics system has been used with three spin-entry research models. Mechanical limitations of aircraft control surfaces and automatic spin-prevention techniques were successfully simulated within the radio control system. The control laws for the models were changed from flight to flight, which allowed data to be gathered quickly on a number of different control strategies. The utility of this system has been demonstrated in flight tests for a period of over a year.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., September 12, 1973.

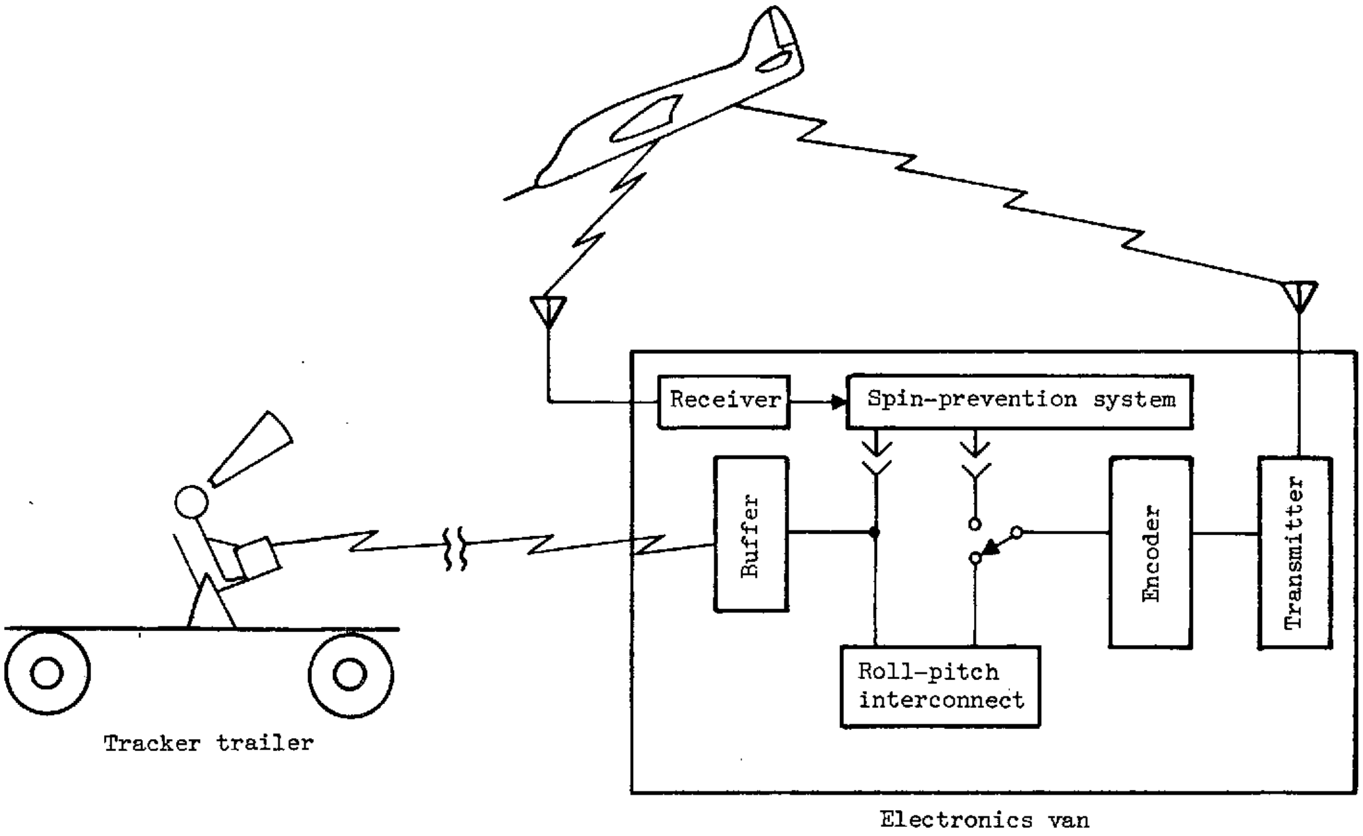


Figure 1.- Radio-control-system ground electronics configuration.

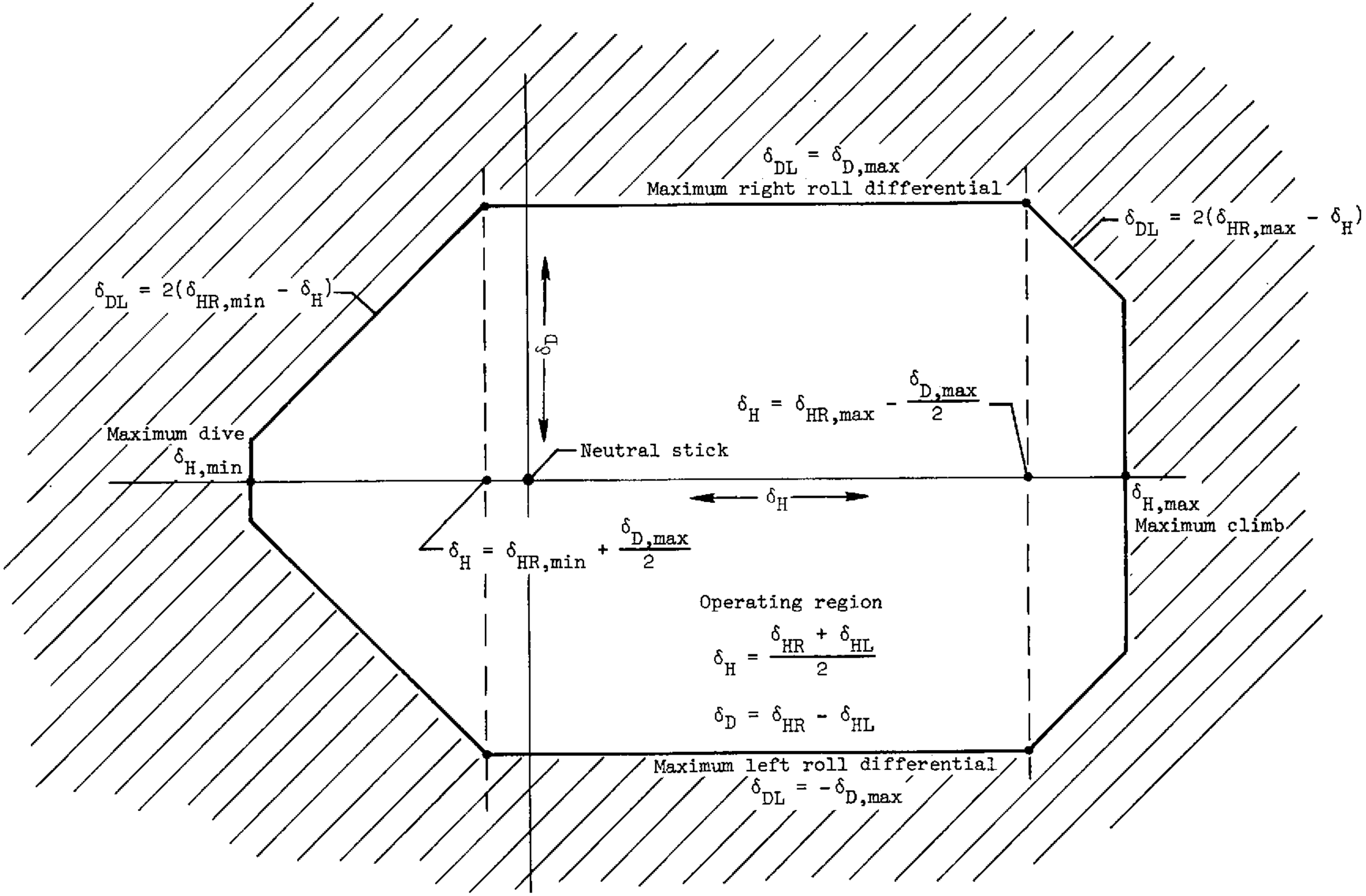


Figure 2.- Limit envelope for differential/collective stabilator movement.

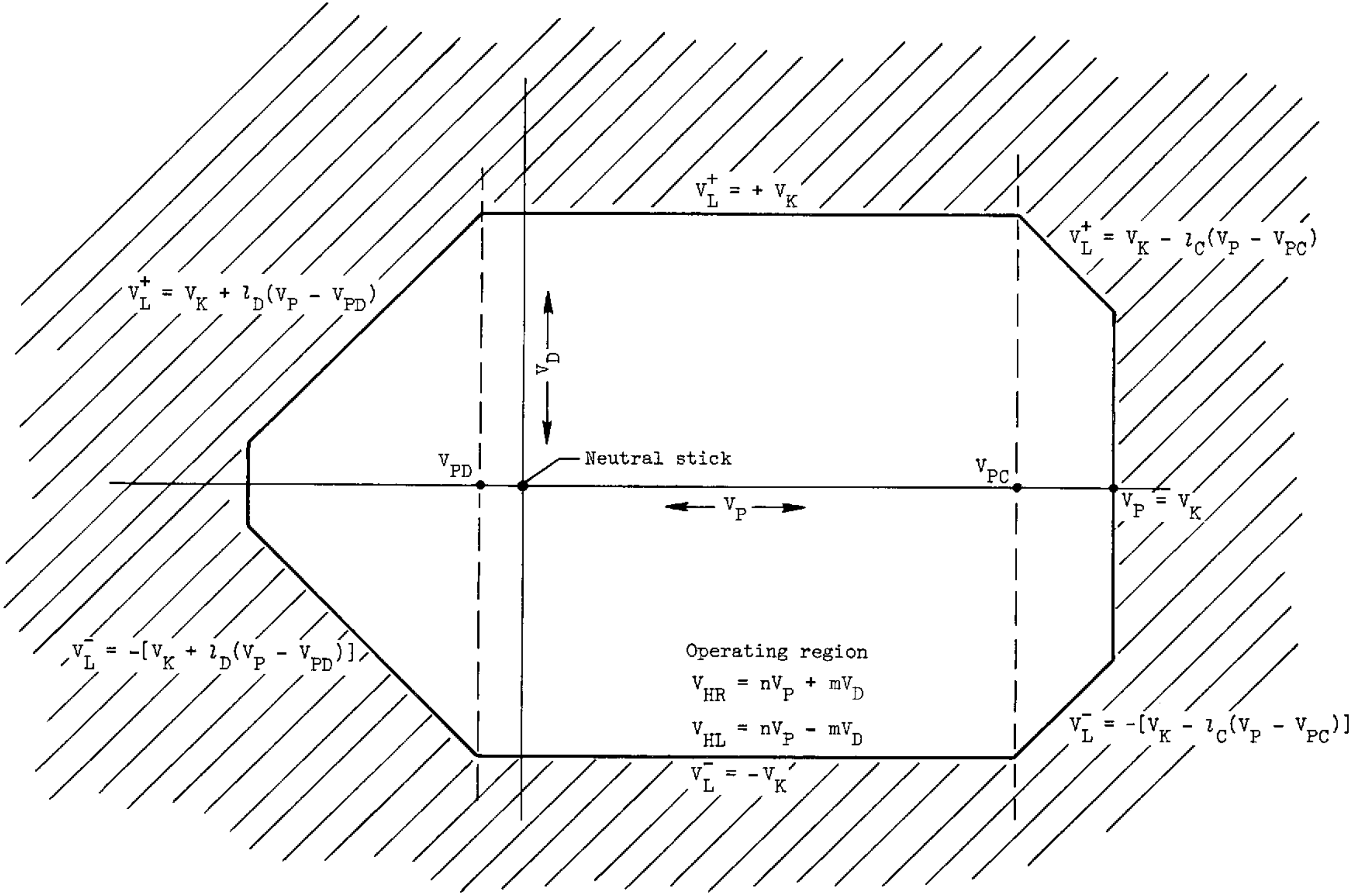


Figure 3.- Voltage limit envelope for stabilators.

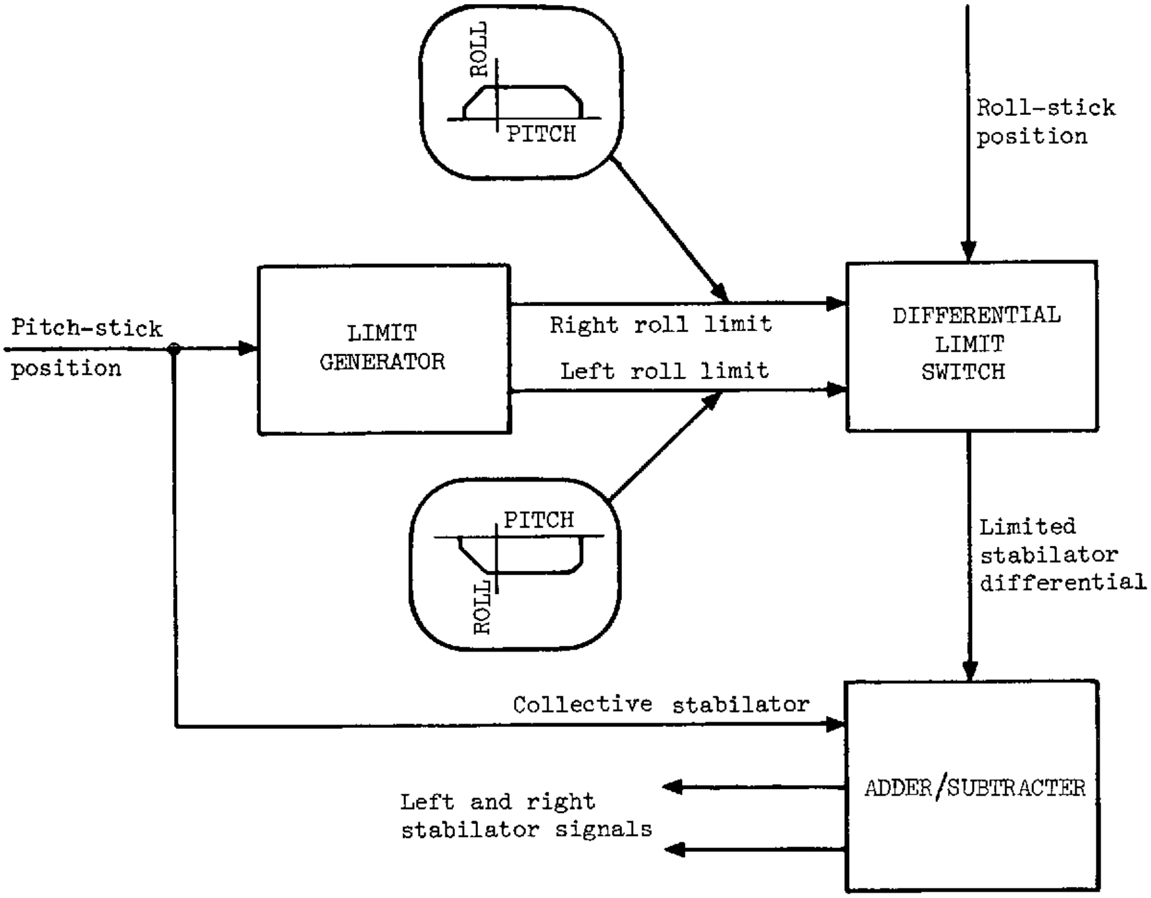


Figure 4.- Roll-pitch interconnect.

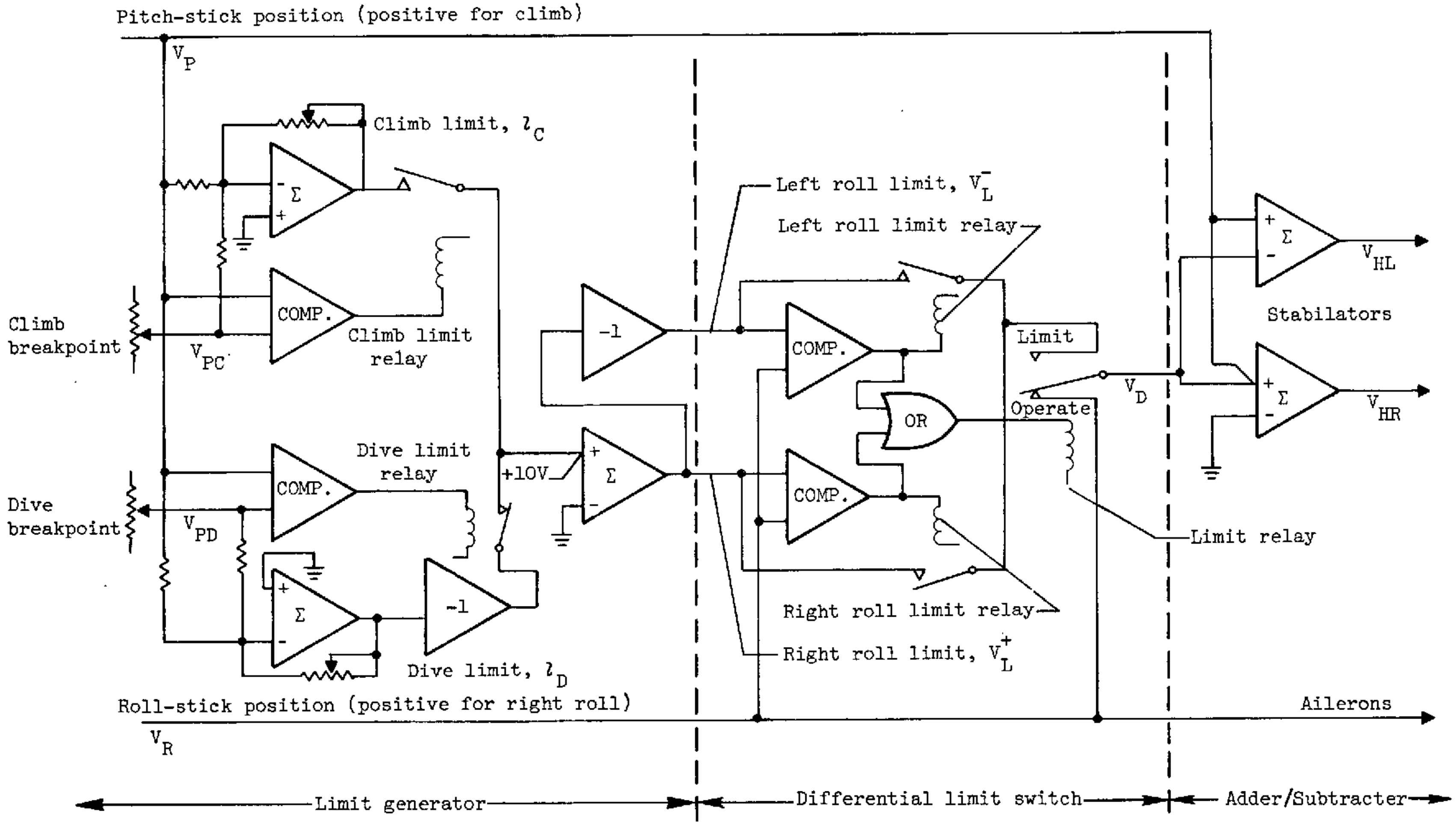
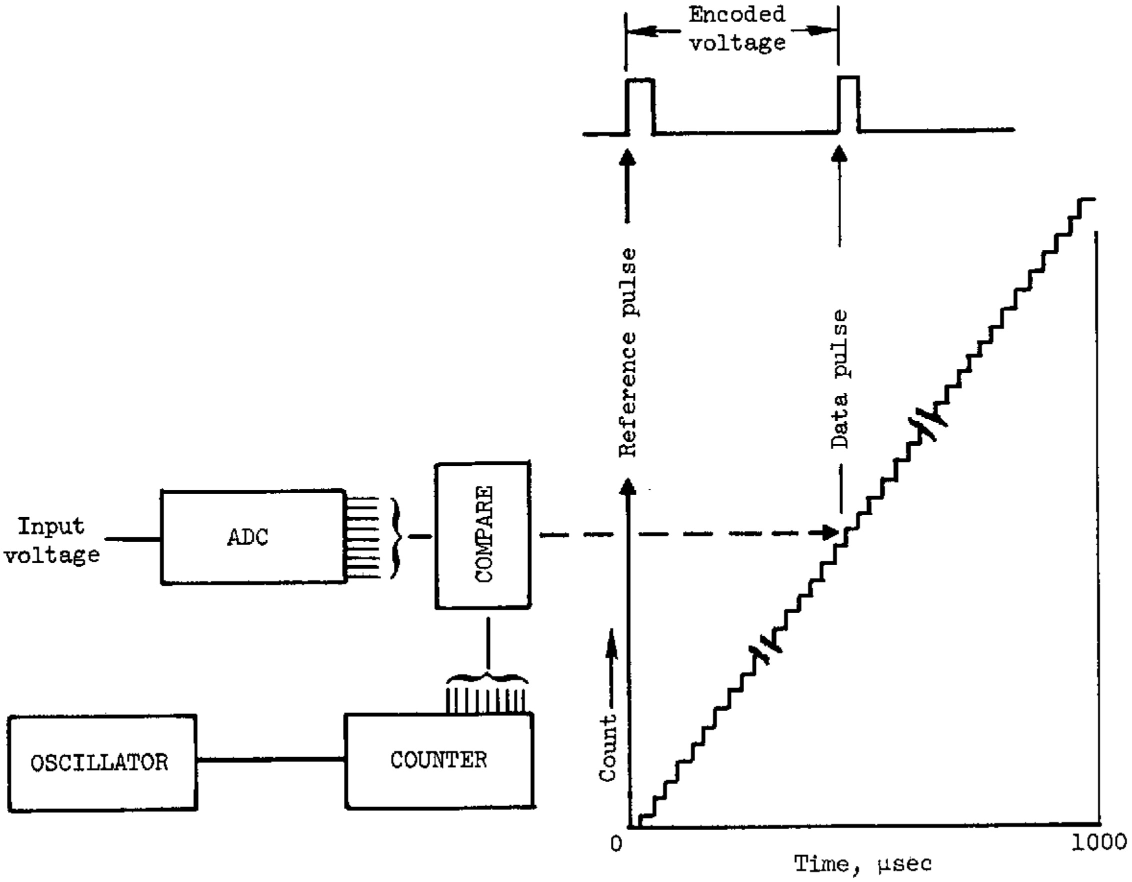
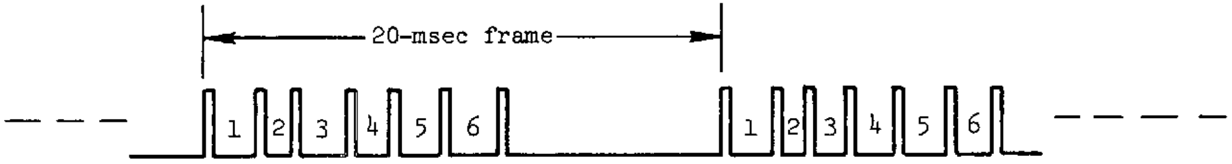


Figure 5.- Roll-pitch-interconnect functional circuit diagram.

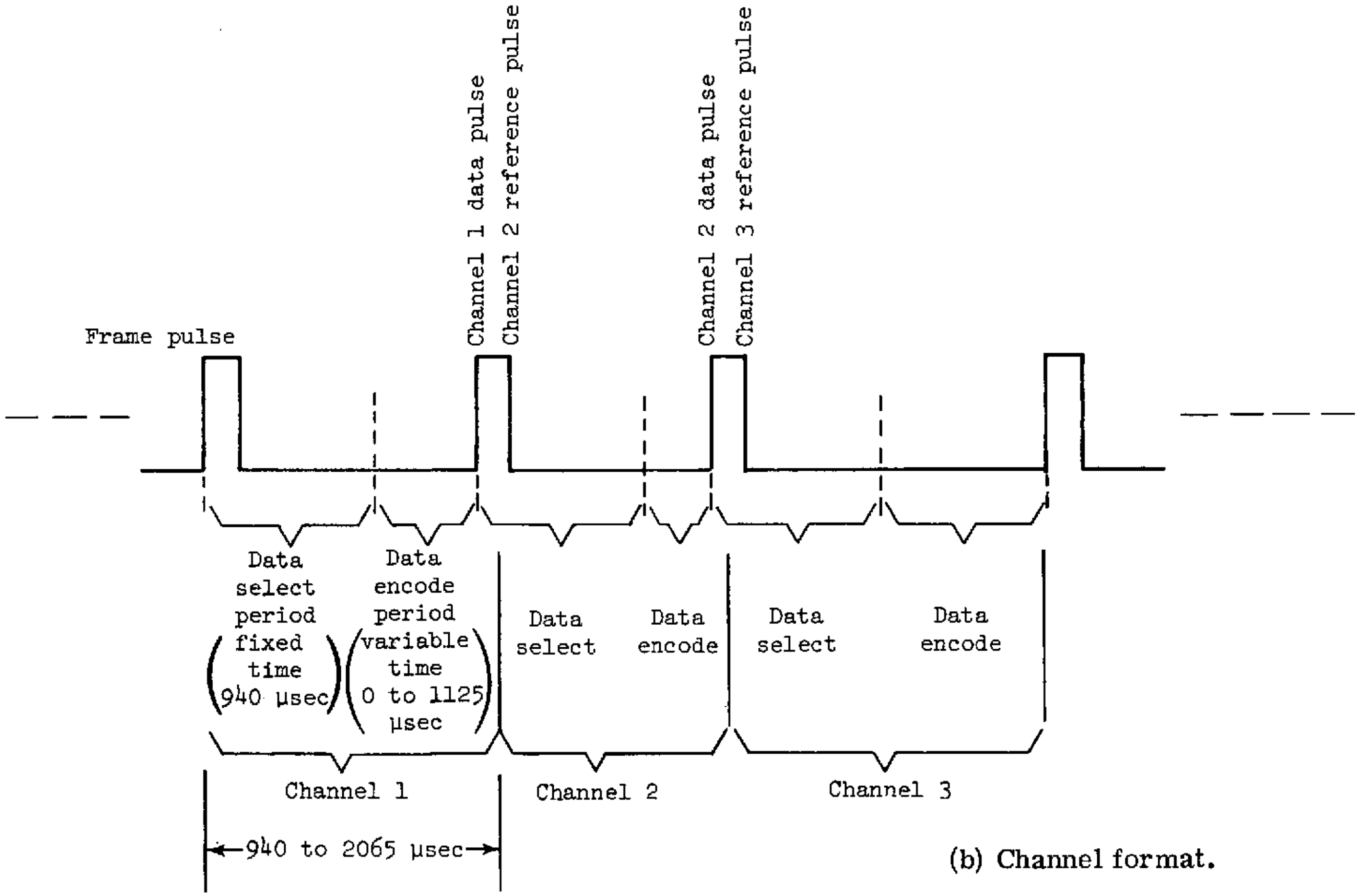


(a) Major blocks. (b) Timing.

Figure 6.- Voltage-controlled time interval generator.



(a) Frame format.



(b) Channel format.

Figure 7.- Data format.

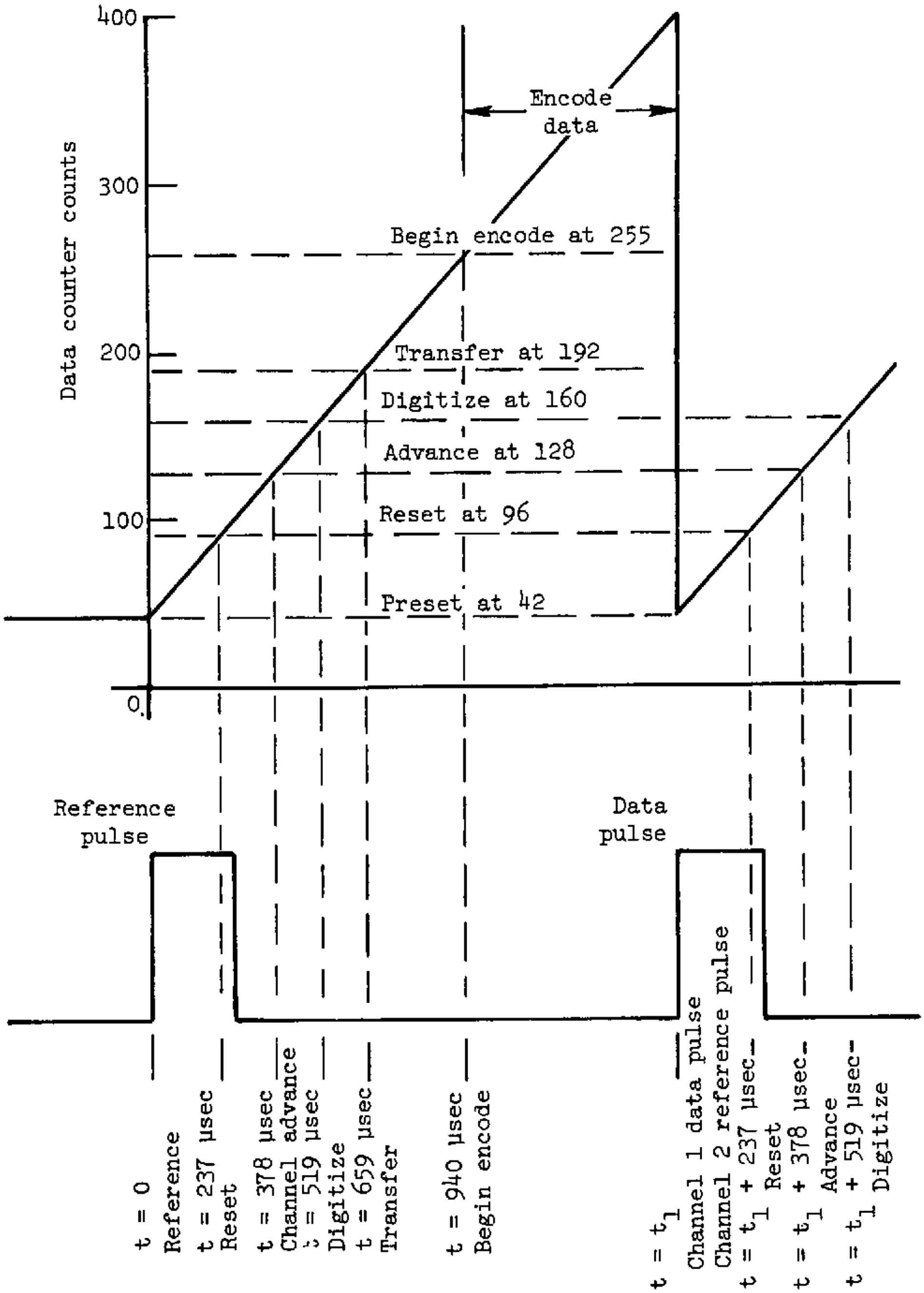


Figure 8.- Encoder sequence.

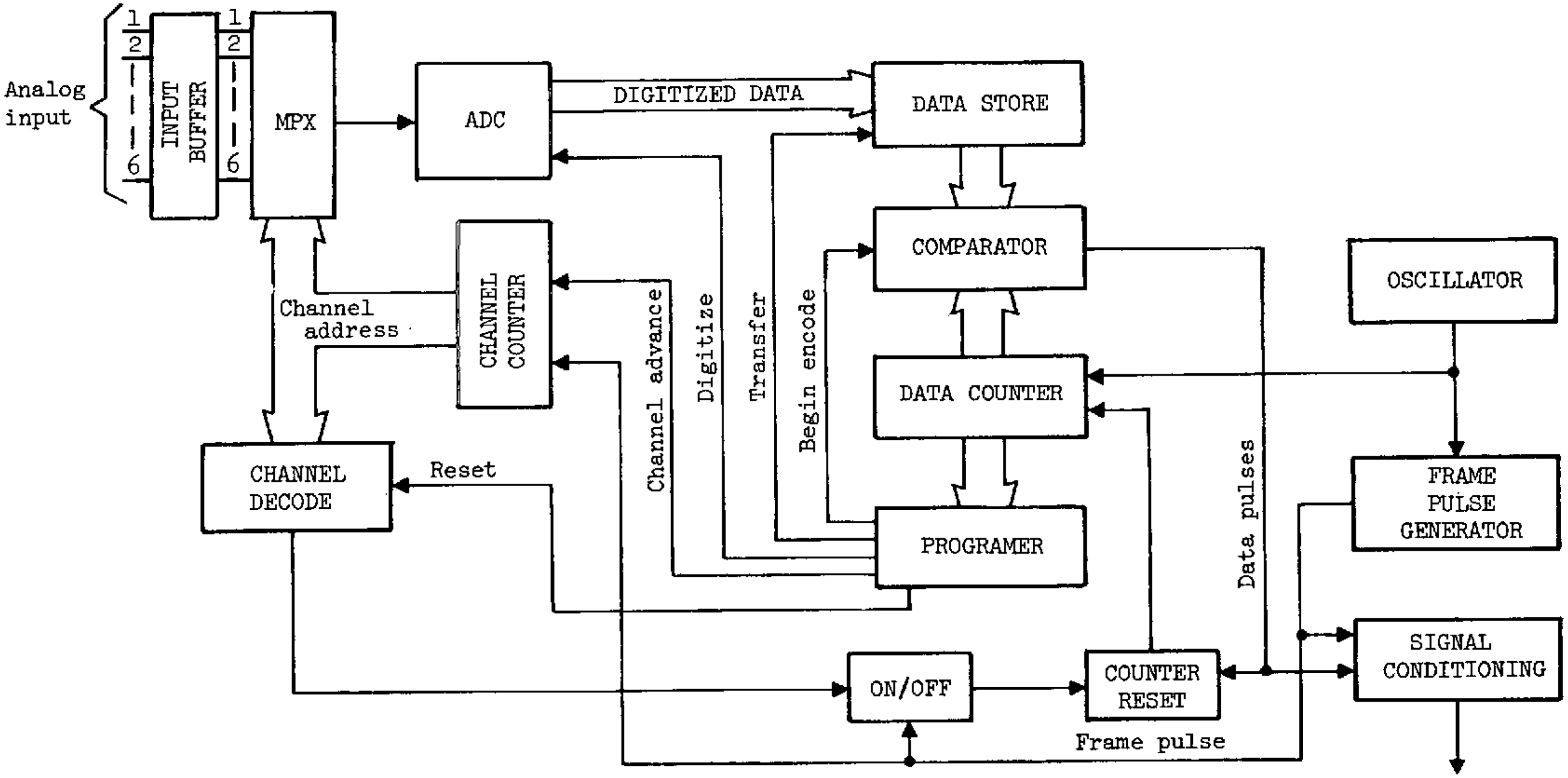


Figure 9.- Encoder block diagram.

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