Electron Beam Deflection Tube for Pulse Code Modulation

By R. W. SEARS

Introduction

PULSE code transmission systems[1] in which successive signal amplitude samples are transmitted by pulse code groups require special modulators. The essential operational requirements of a pulse code modulator are: (1) to quantize or measure the signal amplitude sample to the nearest step in the discrete amplitude scale transmitted by the pulse code system, and (2) to generate the group of on-off pulses identifying the step.

Several methods have been proposed[2, 3, 4] in which quantization and pulse formation were performed with circuits employing conventional electron tubes. The circuits involved sequential and comparison operations and were not easily adapted to a multi-channel time division system because of limitations in coding speeds and the complexity of the equipment. An electron beam deflection tube has been developed which, together with associated beam positioning and sweep circuits, performs the modulation rapidly, making possible the sequential modulation of a number of channels in time division multiplex.

The electronic principles, design and characteristics of the experimental tube are described in the present paper.

Conversion from Signal Input to Pulse Code Output

An electrical input voltage may be converted into an output code pulse group with the electron beam deflection tube shown in Fig. 1a. An aperture or code masking plate is arranged perpendicular to the axis of the electron gun at the focal point. The coordinates of the aperture plate are aligned with the deflection axes of the X and Y deflector plate pairs. The electron beam strikes the output plate when it passes through an opening in the aperture plate.

An input voltage of appropriate value applied to the Y deflector plates will deflect the beam to point "*a*" of the aperture plate as indicated in Fig. 1a. A linear sweep voltage applied to the X deflection plates, while the

[1] An Experimental Multi-Channel Pulse Code Modulation System of Toll Quality, L. A. Meacham and E. Peterson, this issue.
[2] A. H. Reeves, *U. S. Patent* #2,272,070, Feb. 3, 1942.
[3] H. S. Black and J. O. Edson, paper presented June 11, 1947 at A. I. E. E. meeting; Montreal, Canada.
[4] W. M. Goodall, *Bell System Technical Journal*, July 1947.

input voltage on the *Y* deflection plates is held constant, causes the electron beam to sweep across the aperture plate along the dashed line *a-b*. A time sequence of output pulses is produced at the output plate when the beam passes through the apertures of the code p`ate along the path *a-b*.

A series of output pulses or a "pulse group" is characterized by the presence of pulses at time positions corresponding to the several vertical columns of apertures. The code plate shown in Fig. 1 is laid out in accordance with

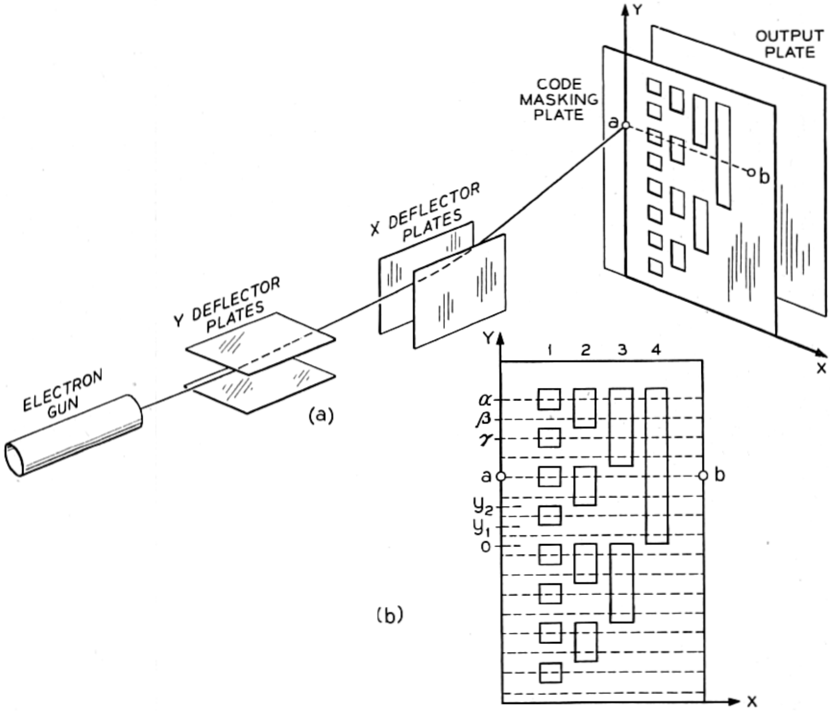

Fig. 1—Electron beam deflection tube for coding.

the binary number system pattern[5] which was chosen for the present pulse code work because of the simplicity of decoding. The four-digit code plate shown in the tube of Fig. 1 provides for coding only 16 amplitude values and was used to facilitate the illustration. The tube developed for the ex-

[5] The four vertical columns of the four-digit code plate in Fig. 1b provide four positions in time for output pulses. Vertical columns marked 1, 2, 3 and 4 correspond to the first, second, third and fourth digits, respectively, of the pulse code transmitted. Pulses located in time in accordance with this notation are given "weights" of 1, 2, 4 and 8, respectively. Sixteen pulse group combinations are indicated by the 16 dashed horizontal lines in Fig. 1b. The pulse group defined by beam sweep α corresponds to a total "weight" of 15; beam positions β and γ correspond to total "weights" of 14 and 13, respectively, and so on, with the bottom horizontal dashed line in the figure corresponding to zero.

perimental pulse code system uses a seven-digit code plate which provides for coding 128 amplitude values.

The vertical distances between the centers of successive code sweep positions (horizontal dashed lines in Fig. 1b) are made equal so that the codes are spaced by equal input voltage steps. A continuous range of input signal amplitudes will result in a continuous range of horizontal sweep positions. With an infinitely small electron beam, input signal amplitudes in the range from o to y_1 will produce a single output pulse group and input signal sample amplitudes from y_1 to y_2 will produce another output pulse group. This process of dividing the total input amplitude range into finite steps and arranging that input voltages falling within each step produce one and only one output pulse group is called quantization.

The tube of Fig. 1 will only quantize effectively if the electron beam is infinitely small and the sweep and aperture plate axes are aligned exactly. With a finite beam size, there will be sweep positions for which the beam straddles and sweeps out a combination of two adjacent codes.

Precise quantization and a uniform pulse output are required. The problems of quantizing, alignment and uniform pulse output have been solved by the use of a wire grid, called the quantizing grid, located in front of the aperture plate.

Quantization of Beam Position by Feedback

The quantizing grid consists of a horizontal array of grid wires aligned parallel to the code sweep or X axis of the aperture plate. The grid spacings and alignment are such that a wire lies between each adjacent pair of code groups as viewed from the various incident angles of the deflected electron beam. The quantizing grid, by means of an electrical feedback path to the signal deflection plates, divides the input signal range into a number of equal steps and positions the electron beam to the proper level for the code corresponding to the voltage step within which the signal amplitude sample falls. The quantizing grid wires also constrain the electron beam during the formation of the output code pulses, so that it must sweep out the code initially selected. In general, wires or shaped electrodes of any sort located where the electron beam can impinge thereon and connected in feedback relation to the deflection system constrains the electron beam to move in patterns prescribed by these electrodes and are thus called beam guides.

The coding tube with quantizing grid and feedback circuit is shown schematically in Fig. 2. The electrode line-up, reading from left to right in the figure, consists of an electron gun, deflection system, secondary electron collector, quantizing grid, aperture plate and output plate.

For the present purpose, a consideration of the collector and output plate electrodes is omitted and it is assumed that the grid does not emit secondary electrons when bombarded. Electrons which strike the grid produce a current in the grid circuit while electrons that miss the grid have no effect in the grid circuit. The electron beam current intercepted by the grid will be dependent on the y deflection or position of the electron beam. The current is a maximum when the beam is centered on a grid wire and a minimum when it is centered between two grid wires and varies with beam position as indicated by the curve in the lower portion of Fig. 3. The curve is constructed for the case in which the beam diameter is slightly greater than the space between two grid wires. The current to the grid never becomes zero for any beam position. It may be thought of as having a "d-c. component" B. Amplifier 2 in Fig. 2 introduces a bias which cancels this "d-c. component" so that the feedback voltage is symmetrical about zero.

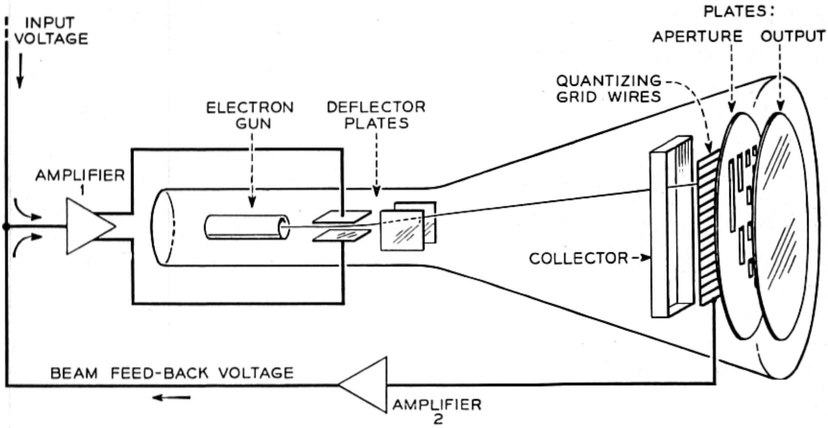

Fig. 2—Coding tube with quantizing grid and circuit schematic.

The grid current is amplified and the voltage developed is applied in feedback relation to the Y deflection plates as shown in Fig. 2. The case in which a positive feedback potential deflects the beam in the same direction as that for a positive signal voltage will be considered.

The beam deflecting voltage is equal to the sum of signal and feedback voltages and the beam position is a linear function of the deflection voltage so we may write

$$-e + Dy = e_f \tag{1}$$

where e is the input signal voltage, D the deflection constant, y the beam deflection or position and e_f the feedback voltage. The feedback voltage e_f is a periodic function of beam position y. Equation 1 therefore defines equilibrium beam positions for input signal voltage e. Equilibrium beam positions in accordance with Equation 1 are determined graphically in the top portion of Fig. 3. The feedback voltage representing the right-hand side of Equation 1 is plotted as a function of beam position. The electron beam will have several possible positions of equilibrium at points (*p*1, *p*2, *p*3, *p*4, *p*5, *p*6 and *p*7) where the deflection line *D* erected from $-e$, representing the left-hand portion of Equation 1, crosses the feedback curve. These are the only beam positions for which the deflection potential (signal plus feedback) attains correct values for corresponding beam positions.

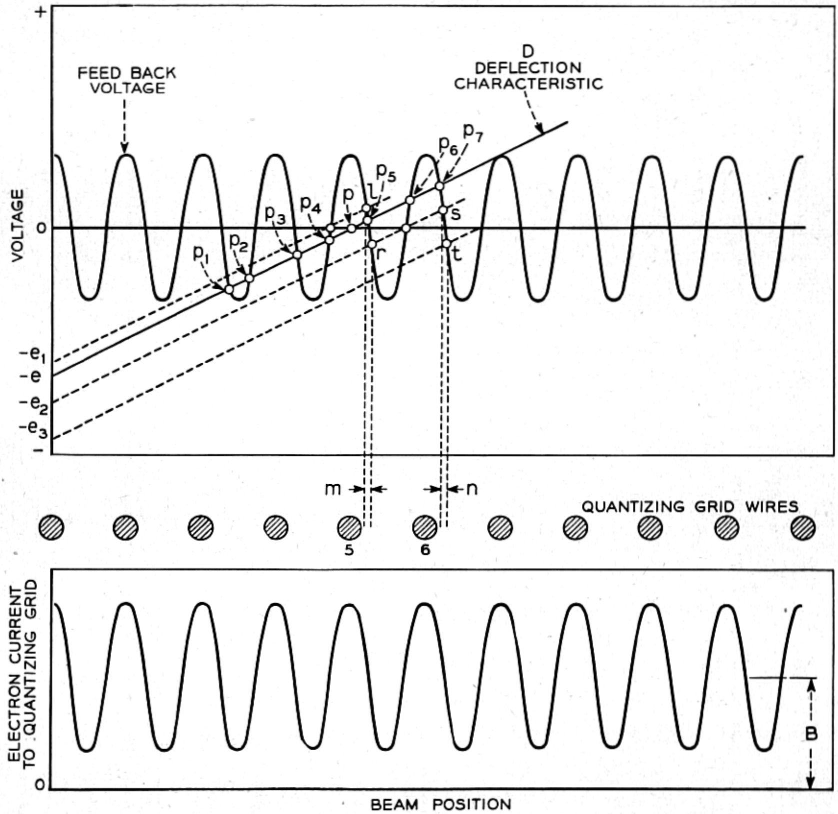

Fig. 3—Graphical representation of quantization.

However, only positions *p*1, *p*3, *p*5 and *p*7 will be in a true state of equilibrium. This can be seen as follows: Consider the beam at point *p*3; if the beam is perturbed toward the right, the feedback voltage tending to deflect the beam to the left increases. The opposite action ensues if the beam is perturbed in the left-hand direction. Point *p*3 is a true equilibrium point. On the other hand, consider the beam at position *p*4. If the beam is perturbed to the right, the feedback voltage tending to deflect it to the right increases and the beam continues to move until it reaches the equilibrium position $p5$. If the beam is perturbed to the left from position $p4$ it will continue to move to the left until it reaches position $p3$.

The number of possible equilibrium beam positions for an input signal sample depends on the maximum values of the feedback voltage and the slope of the deflection characteristic. It is necessary that only one equilibrium beam position be available for a particular small range of signal voltage. This can be achieved as follows: if a signal voltage e is established with the feedback circuit inoperative, the beam will be at a position p, Fig. 3. When the feedback circuit is activated with the signal voltage held at e, the beam will move from p to $p5$. With this procedure, signals in the range from e_1 to e_2 will result in equilibrium beam positions between points l and r on the curve. Thus, for signal voltages within the range from e_1 to e_2 the beam will fall in the small spacial interval m, whereas beam positions for input signals in the same range without feedback would vary from grid wire 5 to grid wire 6. Likewise, signal voltages between e_2 and e_3 will cause the beam to assume positions between s and t in the spacial interval n. The electron beam may be thought of as "leaning" on one side of a grid wire for a finite signal voltage range and on the same side of the next grid wire for an adjacent signal voltage range.

If the feedback voltage is of the opposite polarity to that assumed above, the quantizing action proceeds in the same manner except that the quantized beam positions lie at the left of the wires. The beam may be thought of as "leaning" on the opposite side of the grid wire.

The proper quantizing action is obtained by establishing and holding the signal voltage with the feedback circuit inoperative and then activating this circuit. The feedback circuit may be deactivated and activated by either (a) blanking and deblanking the electron beam, or (b) defocusing and focusing the electron beam by applying the proper voltage change to the beam control or focusing electrodes of the gun, respectively.

Since the grid wires are parallel to the horizontal rows of aperture holes, the feedback action constrains the beam to sweep out the code group initially selected even though the sweep axis is tilted slightly with respect to the grid wires and aperture plate. The maximum swing of the feedback voltage at the deflection plates should be about three or four times the value of the voltage required to deflect the beam from one code group to the next in order to provide ample protection against the beam jumping from one code group to the next code group during the sweep.

THE EXPERIMENTAL CODING TUBE

The seven-digit experimental tube developed for pulse code transmission system trials utilizing the electrode lineup shown schematically in Fig. 2 is pictured in Fig. 4. The electron gun assembly and the target plate assembly

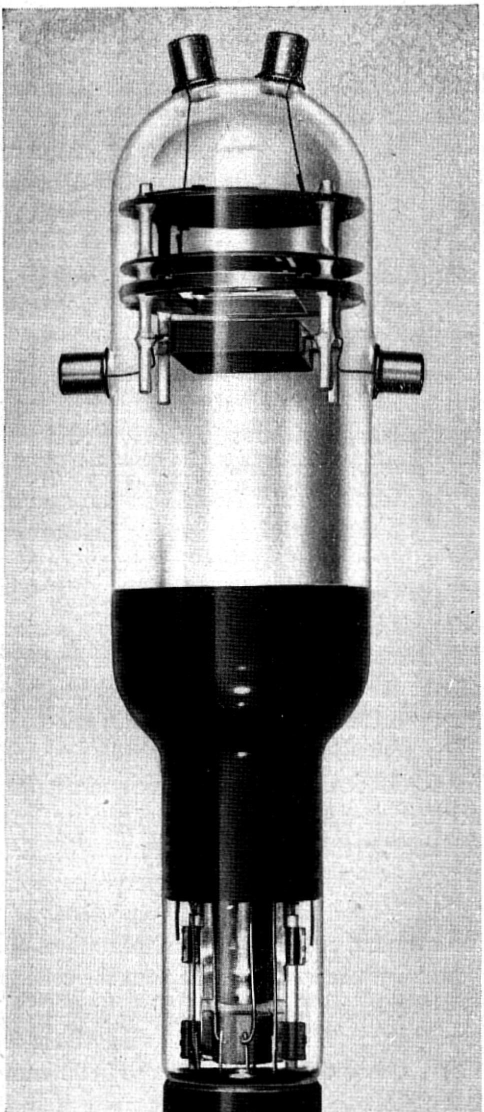

Fig. 4—Experimental seven-digit coding tube.

are sealed in at opposite ends of the tube envelope. The over-all length of the tube is $11\frac{1}{4}''$ with a maximum bulb diameter of $2\frac{1}{4}''$.

The electron gun operates at a final anode potential of 1000 volts with a beam current of approximately 10 microamperes. A potential of about 100 volts applied to the signal input deflection plates deflects the beam from the center to the top of the aperture plate. This corresponds to a maximum deflection angle of $10\frac{1}{2}°$.

The four electrodes of the target assembly, secondary collector, quantizing grid, aperture plate and output plate are shown in the photograph of Fig. 5 from bottom to top respectively. The secondary collector is a simple rectangular shaped electrode. The quantizing grid consists of a circular frame with a parallel array of grid wires stretched across a rectangular opening. The aperture plate is a thin disc with apertures arranged in a binary pattern which provides for a seven-digit code. The output plate is a thin circular disc. Both aperture and output plates are coated with a carbon layer to suppress secondary electron emission from their surfaces.

The parts of the target assembly are held in accurate alignment in a jig and cemented and held in position on four ceramic rods. The entire assembly is held rigidly in the tube envelope by means of spacers attached to the quantizing grid and output plate.

The target assembly is aligned with the electron gun and deflection plate axes by means of lineup tools in the glass lathe at the time the final seal is made at the center of the glass envelope. It has been possible to hold the alignment of the deflection axes with the aperture plate to within slightly less than 1° with this construction.

The construction of the quantizing grid may be seen more clearly in the photograph of Fig. 6. The grid frame has raised portions on two sides of the rectangular opening. These are milled with a series of grooves for each grid wire. The grid laterals are affixed in the grooves by brazing and are thus accurately spaced with respect to each other and to assembly lineup holes which can be seen spaced around the edge of the grid frame. The wires are held taut by means of a flat spring which is welded to the grid frame and supplies tension to stretch the lateral wires. The grid wires are 4.0 mils in diameter, processed to have a secondary emission coefficient of about 3. The laterals are spaced 11.6 mils between centers.

The openings in the aperture plate are made by a punching operation. The area of the aperture plate covered by the first and second digit columns is milled to a thickness of 5 mils in order to facilitate accurate punching of the smallest apertures. The apertures in the first digit column (bottom horizontal row in Fig. 5) are rectangular .012″ x .062″. The seven-digit code pattern provides 128 different output pulse groups. The wide openings

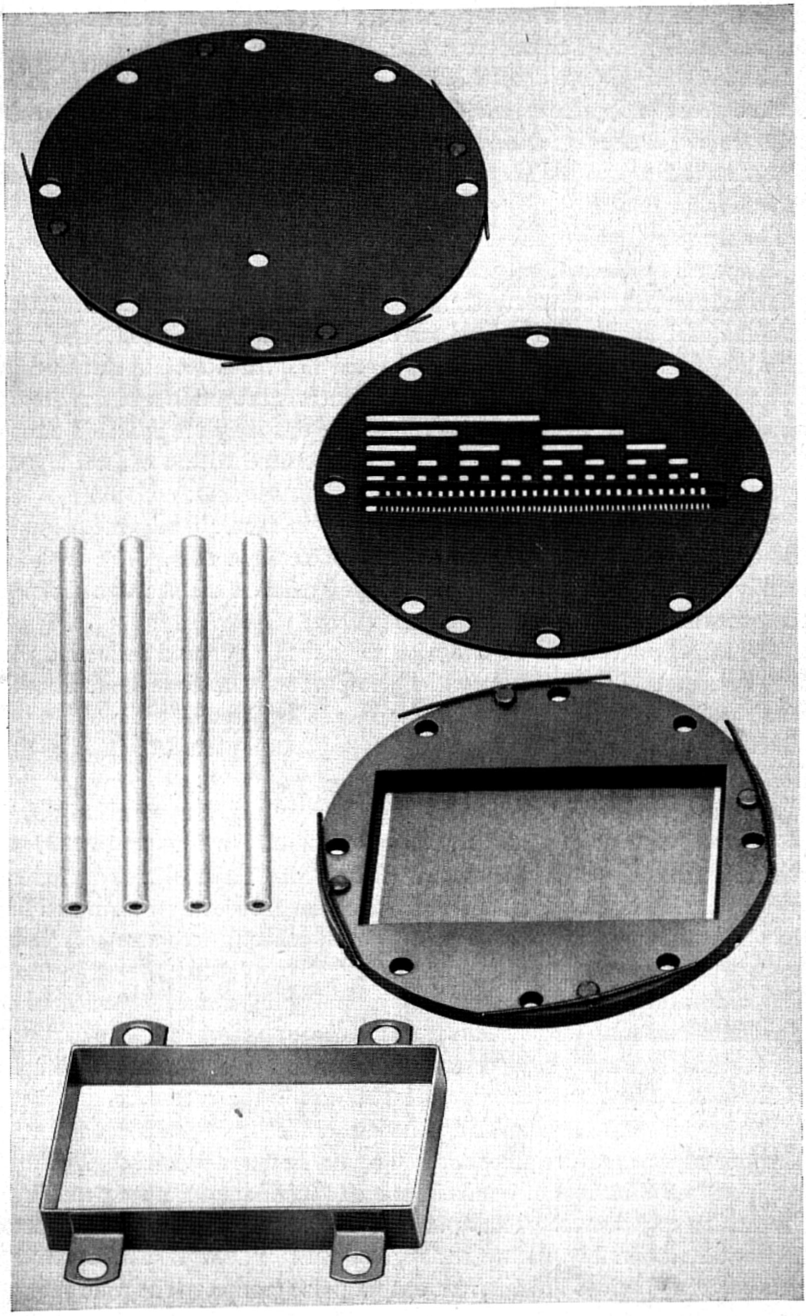

Fig. 5—Target electrodes.

at the left hand side of the aperture plate in Fig. 5 provide a peak amplitude range for which the output pulse group consists of all seven pulses. This in effect provides a peak limiting action.

Leads from the four electrodes of the target assembly are brought out directly to terminal caps on the side and end of the tube envelope to decrease the interelectrode capacitances and to facilitate direct connection to external circuits.

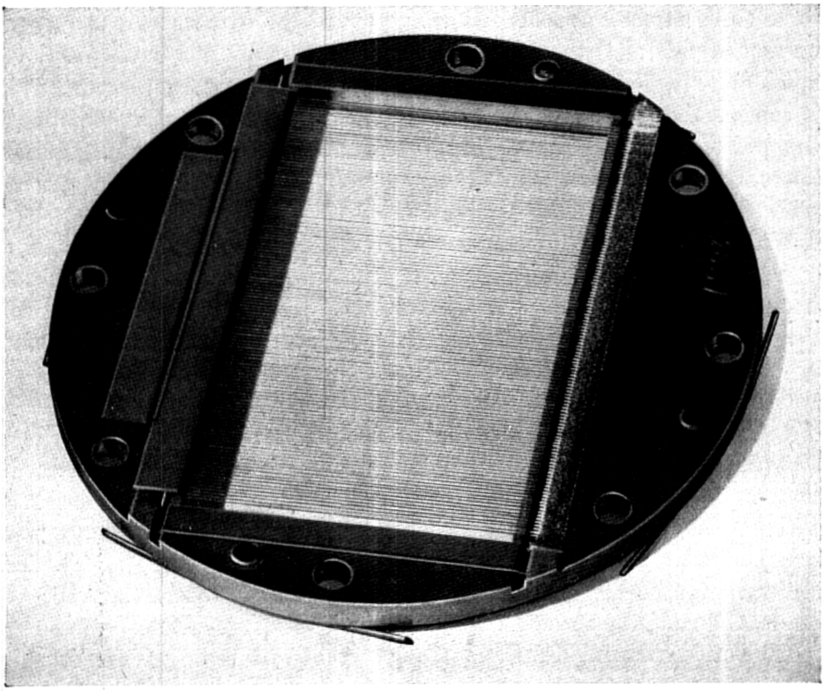

Fig. 6—Quantizing grid.

Operational and Design Considerations

The quantizing action depends on the periodic variation of electron beam current intercepted by the wires of the quantizing grid with beam position. Secondary electron emission from the grid and other electrodes was assumed to be negligible with the feedback circuit connected directly to the quantizing grid as shown in Fig. 2. The uniform suppression of secondary electrons is difficult to achieve even though the grid is coated and processed for a low secondary ratio. It is also difficult to prevent secondary electrons produced at the aperture plate from being collected by the grid.

A preferred method of operation utilizes the secondary electrons produced at the grid by the impinging primary beam for the quantizing action rather than the directly intercepted electron current as heretofore assumed. The secondary electron collector located in front of the quantizing grid is maintained at a positive potential and collects most of the secondaries from the grid. There is, of course, a correspondence between the secondary electron current and the fraction of the beam current intercepted by the grid wires. The quantizing circuit is made by connecting the feedback path to the secondary collector and the quantizing action proceeds as described heretofore. This method has the following advantages over the direct primary current method: (1) the collector current as a function of beam position is much more regular; (2) the swing between maximum and minimum current is considerably larger because of the secondary emission multiplication at the grid surface; and (3) the capacitance between collector and ground is lower than the capacitance between the closely spaced grid and aperture plate.

With secondary electron current feedback, the aperture plate is operated at a positive potential relative to the grid to suppress secondary electrons from the aperture plate. The proportion of the secondary emission from the grid collected by the aperture plate is small compared with that collected by the secondary collector. High velocity secondaries originating at the aperture plate are, however, able to penetrate the retarding field and strike the grid. These energetic secondaries produce low-velocity secondaries at the grid which flow to the secondary collector electrode. This alters the character of the secondary collector current in accordance with the spacial pattern of the apertures in the code plate. The surface of the aperture plate is carbonized to reduce the emission of high-velocity secondaries. The spacial variation of the quantizing current is reduced to less than 10% of the total quantizing current swing with this treatment.

The periodic nature of the quantizing current with beam position must be as uniform as possible as regards both the "a-c" and "d-c" components. The maximum swing should also be as large as possible to permit the use of the lowest possible impedance in the feedback path to obtain a wideband characteristic for fast coding.

The factors which determine the maximum current swing are electron beam current, secondary emission coefficient of the grid wires, electron beam spot size, grid wire diameter and spacing. The quantized beam falls approximately halfway between the center of a grid wire and the midpoint between wires. The beam must be small enough that its edge does not extend into the region beyond the wire on which it "leans" by an appreciable amount. This is obtained with the electron beam focused to a spot slightly smaller than that for maximum quantizing current amplitude.

Optimum performance has been obtained with the electron beam focused to a radius[6] of about 5 mils for the grid spacings previously specified.

The principal irregularities in the periodic quantizing current are caused by variations in secondary emission coefficient of the grid and aperture plate and deflection defocusing of the electron beam. The secondary emission from the grid surface can be made sufficiently uniform by careful processing. This is illustrated in Fig. 7 which is a trace of an oscilloscope

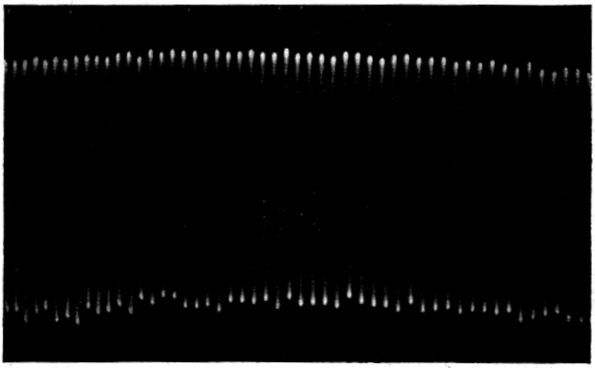

Fig. 7—Variation of quantizing current with beam deflection.

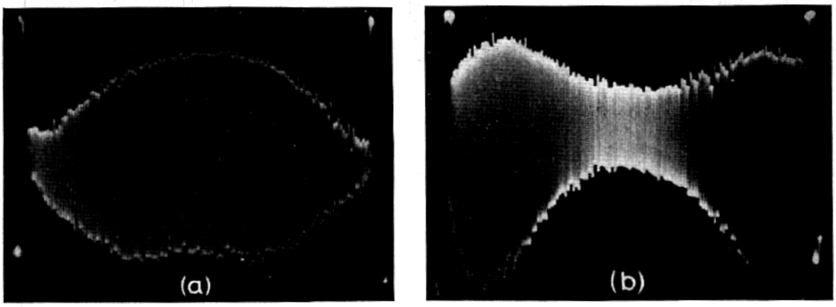

Fig. 8—Deflection defocussing.

presentation of the secondary collector current as the beam is deflected by a linear sweep at right angles to the grid laterals. The trace was limited to cover a sufficiently small number of wires to show details of its shape. Figure 8a illustrates the effect of deflection defocusing. The sweep was expanded to cover all of the grid wires and the electron beam focused for maximum amplitude in the center region. The curve is so compressed that

[6] Distance from the center of the beam to a point at which the electron current density is 5% of its value at the center.

the individual oscillations of the current between maximum and minimum values can hardly be resolved. The envelope of the curve indicates the extent to which the swing is reduced at the two ends by the increase in electron beam spot size which results from deflection defocusing. In Fig. 8b, the focusing voltage has been changed by 12 volts and it can be seen that the beam is in focus at the maximum deflection angles and out of focus in the center region. With an intermediate or compromise focus voltage, the tube will quantize satisfactorily over the entire code range. Best results have been obtained with the tube in the experimental pulse code system by the use of a simple circuit which changes the focus voltage in a linear manner with the rectified or absolute value of the input deflecting signal thus compensating for the deflection defocusing of the tube.

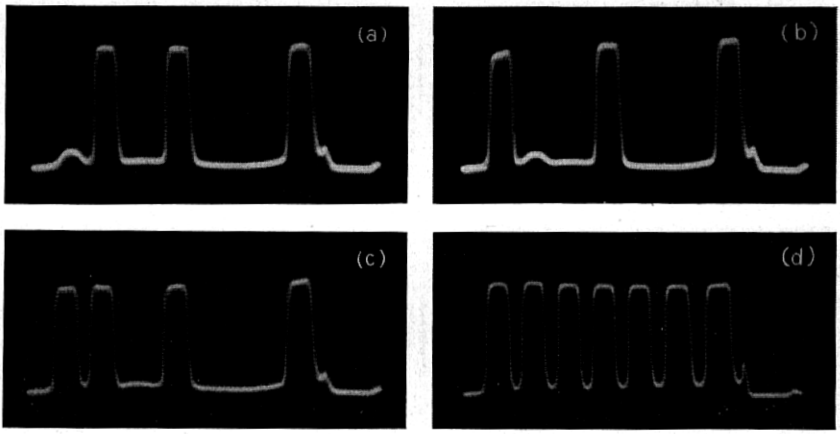

Fig. 9—Typical pulse code outputs.

The output plate is usually operated at a positive potential relative to the aperture plate with attendant suppression of secondary emission from the former. Output pulses of opposite polarity may be obtained by operating the output plate at a negative potential and processing this plate to have a secondary emission ratio greater than unity.

The several groups of output pulses shown in Fig. 9 are illustrative of the tube output. Successive digit pulse positions occur from left to right in the figures. The small kink in the base line at the first and second digit pulse positions in codes a and b respectively are small error pulses caused by a small portion of the edge of the beam overlapping a grid wire when the beam is quantized. Error pulses of this magnitude are readily eliminated by slicing when the tube is used in the pulse code transmission system.

Coding tubes have operated satisfactorily for long periods of time in the experimental multi-channel pulse code system and have required minor adjustments of potentials no more than once a day. The tube operates in this equipment with a code sweep time of 10 microseconds.

Acknowledgment

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The development was under the over-all direction of Mr. J. R. Wilson and Dr. S. B. Ingram.