Capacitive keys, simpler circuits add up to reliable keyboard

A 90-key ASCII-coded keyboard has been built at low cost from novel, contactless keys and circuitry that needs only 13 transistors for the job of producing a seven-bit code

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☐ In the race to develop more reliable and economical electronic keyboard assemblies, designers are focusing on improving the keying mechanism and simplifying encoding circuitry. A new keyboard where the design of a novel electrostatic impulse key is directly related to the simplification of the circuitry has been constructed.

The capacitive key needs no mechanical closure and therefore can claim long life and reliability. The circuitry requires only 13 field effect transistors on a printed circuit board, a distinct departure from designs that required either hundreds of diodes or an expensive metal oxide semiconductor chip.

The feature of the key's design that makes it possible to use so few FETs is its ability to send a three part signal to three transistors at once. Each key transmits to a different combination of FETs. These combinations form a subcode which is translated by some logic circuitry into a seven-bit code that is adequate to service the 90-key American Standard Code for Information Interchange (ASCII) keyboard.

The element basic to the key's construction is a thin, dome-shaped metal spring about the size of a dime and arching to a height of about 0.025 inch. (Fig. 3). Three edges are clipped from its base so it sits on three equilaterally spaced points above a conducting target disk electrically insulated from the spring by a film coating. These two elements make a capacitor, which increases in capacitance whenever pressure applied to the dome causes it to buckle with a crisp audible snap, like the sound of a toy "cricket." The target disks are protected by a solder mask material that is silkscreened over the entire pc board. Only the ring upon which the dome spring rests is uncoated.

When a key is struck, the capacitance between the dome and the target doubles its static value of 4 or 5 picofarads in about 100 microseconds. When the key is released, the dome spring quickly recovers its arched position and the capacitance reverts to its static value.

The concept is the same as the one behind a capacitor microphone, in which sound waves cause a diaphragm to vibrate and produce capacitance variations that an amplifier promptly converts into audio frequency signals. But the signal voltage available from the key is much larger than a microphone's

because of the large increase in capacitance. For example, a 150-volt bias and a suitable target load resistance will produce a signal pulse of 15 to 20 volts that lasts about 0.5 millisecond.

The instantaneous relationship between the time-variant capacitance, C, voltage, V, and charge, Q, is

$$Q = CV$$

From this it might be inferred that, when Q is constant, C and V will vary reciprocally, a change in C producing an immediate offsetting change in V. In reality, however, Q continually readjusts as a time-variant function of the circuit parameters, since C is not lossless and current leakage paths exist. Thus, a more accurate expression for the signal voltage, V_S, is

$$V_S = V_B \left(\frac{1}{1 + \frac{1}{nR}} \right) \left[1 - \left(\frac{C_o}{C_o + nt} \right)^{\left(1 + \frac{1}{nR}\right)} \right]$$

where V_B = the dc bias voltage, R = the target load resistance, C_o = the total static capacitance of the key, n = the rate of change of capacitance in farads per second (assumed constant while the key is in motion), and $nt = C_V$ is the incremental snap capacitance of the key.

The signal voltage, V_S, appears while the moving dome spring is varying the capacitance; when the spring becomes stationary, V_S falls off exponentially. Some temporary ringing motion of the spring persists, but is damped by the polyurethane pressure pad that rests on top of the spring. To obtain the required 15-volt pulse, the dome spring must generate a rate of change of capacitance of about 0.1 pF/μs.

The key is in effect an electrostatic impulse transducer, and matching its high impedance of 2.4 megohms to the associated logic circuitry is a necessity. A practical impedance converter (Fig. 1) is an n-channel junction field effect transistor biased well into cutoff. When an impulse key is depressed, its positive going pulse is arranged to drive the gate/source junction of the J-FET into conduction thereby clipping the positive excursion of the pulse at about +0.5 V. Simultaneously with gate conduction, the drain circuit of the J-FET is turned fully on, allowing the
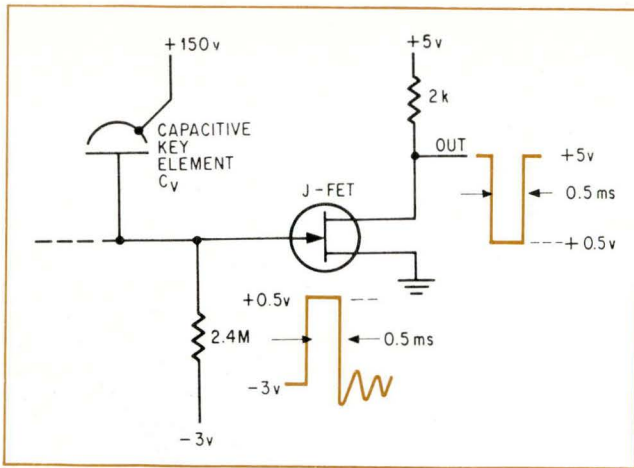
1. Pulse forming. With key at rest, transistor is biased into cutoff. Depressing key abruptly increases key capacitance, driving the field effect transistor into conduction. When the FET is fully on, clipping occurs, limiting pulse's amplitude to $+0.5$ volt. Prescribed change in capacitance restricts pulse width to 0.5 millisecond.
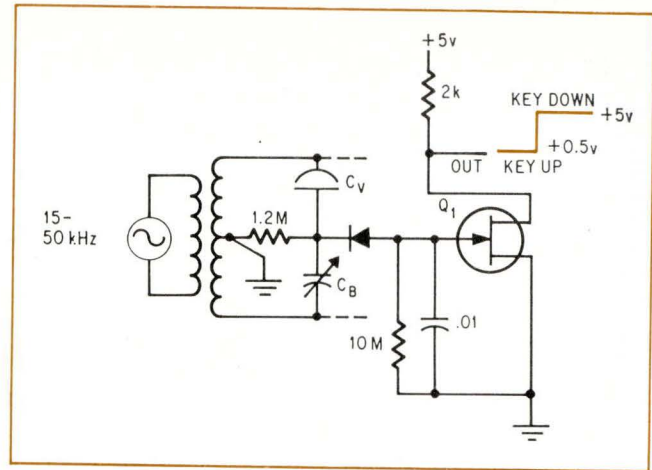
2. Steady output. Control and shift functions require steady output. Key capacitance C_V is balanced in bridge by C_B. When key is depressed, C_V increases, unbalancing bridge, and Q_1 is biased off; result is $+5$ V out until key is released. Frequencies from 15 to 50 kHz usually are available from the dc-to-dc converter that biases the impulse key.

transistor to sink a 2- or 3-mA load, sufficient to drive diode-transistor or transistor-transistor integrated circuit logic loads.

But, the impulse transducer must be able to perform static action as well as impulse action. For, though impulse action is desirable for most of the keys in a keyboard, the output signals of some keys must follow the finger pressure function exactly, just as a dry reed switch stays closed as long as the magnet is held depressed about the reed. Such keys place a keyboard in the shifted mode or generate external control functions.

Static action is achieved by means of an ac capacitance bridge (Fig. 2). The key element acts as one side of the bridge and, when not being operated, has the same capacitance value as the capacitor that forms the other side of the bridge. A 10-volt peak-to-peak signal at a frequency in the 15- to 50-kilohertz range excites the bridge. Such a signal is readily available from the dc-to-dc converter used to bias the impulse keys with $+150$ V.

When the static action key is at rest, the bridge is balanced and generates no output voltage, while the FET is biased at zero voltage and conducts. But for as long as the key is depressed, the bridge is unbalanced and the FET's gate is biased with sufficiently negative voltage to cut off current flow in the drain circuit. Voltage from the depressed shift/control key is about -5 V, from the undepressed key about ±0.2 V.

Since it provides adequate signal voltage—15 V— the target element of the impulse key transducer can be subdivided into three sectors without too great a loss of signal amplitude. It's this sectored target that makes it possible to subcode the several independent signal sources available at each key.
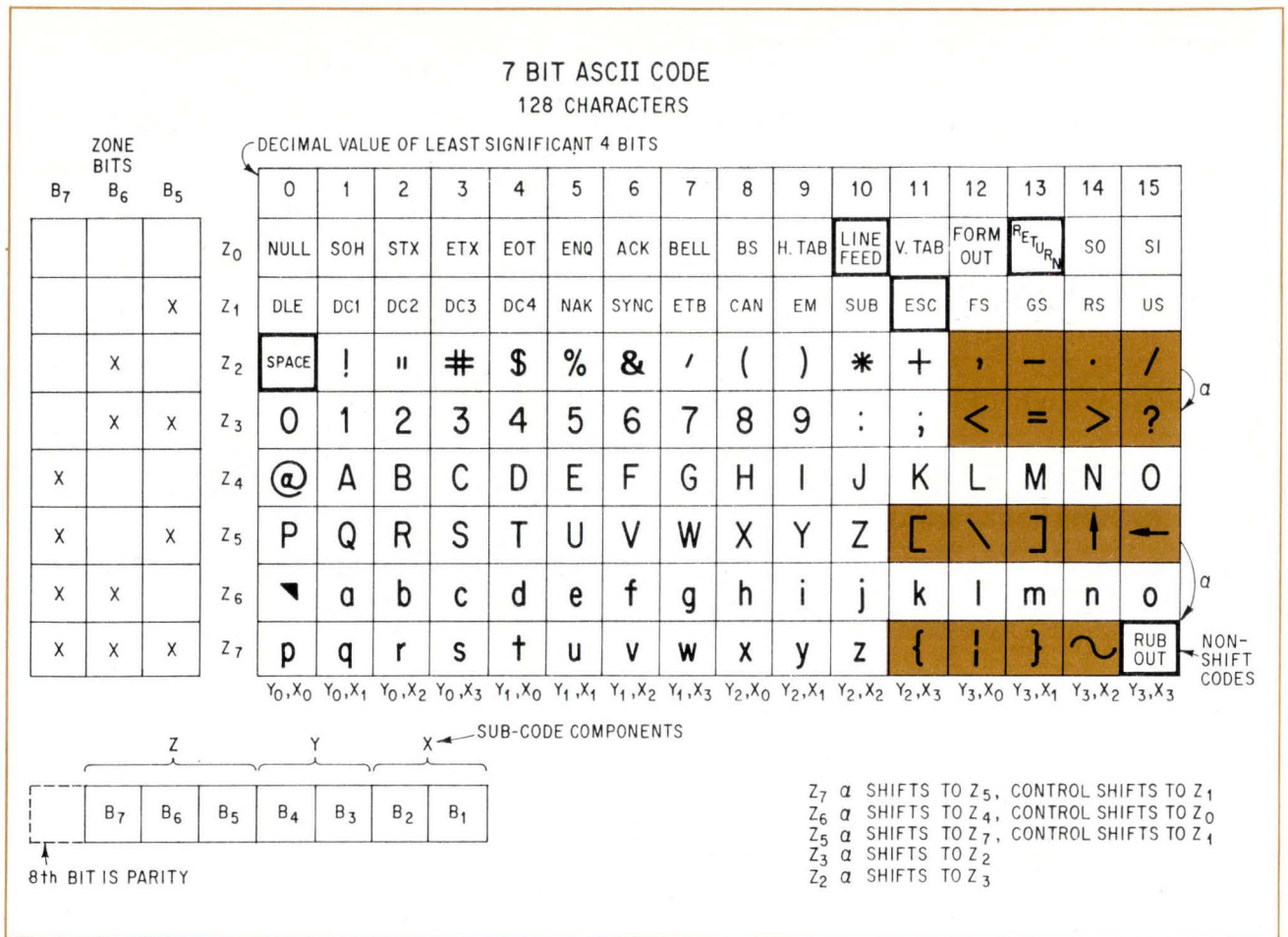
The subcoding arrangement used in this keyboard defines each key of an alphanumeric set in terms of

X, Y, and Z coordinates. These coordinates represent portions of the outgoing bit pattern generated by a typical key—Z represents the first three bits, Y the next two, and X the last two of a 7-bit code. Each of the three target sectors is assigned to one X, one Y, and one Z coordinate line. (Assignment is made during the printed circuit artwork layout of the keyboard and depends on the selected code format.) Each coordinate line is then provided with an impedance transforming FET. This method allows the seven active bits of the ASCII code to be encoded with only 13 transistors, four each for the X and Y axes and five for the Z axis.

The method of subdividing the 7 active bits is shown in Fig. 4. Each X, Y, and Z coordinate line
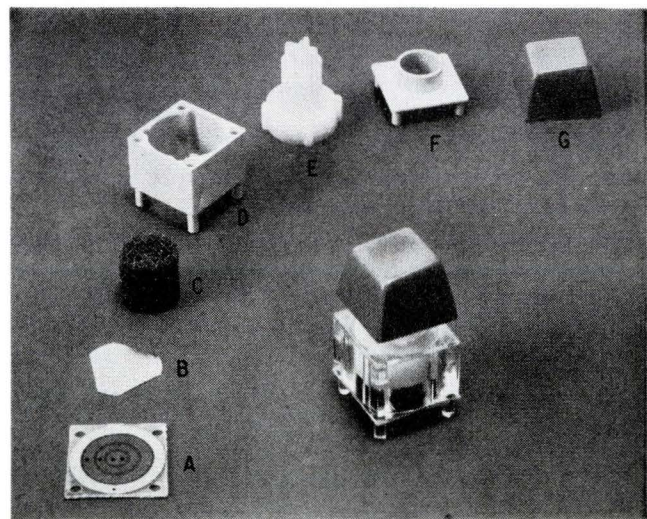
3. Impulse key. Component parts of key are target disk (A), dome spring (B), foam pad (C), key body (D), plunger (E), key lid (F), and key cap (G).

7 BIT ASCII CODE
128 CHARACTERS

ZONE BITS / DECIMAL VALUE OF LEAST SIGNIFICANT 4 BITS

B_7	B_6	B_5		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			Z_0	NULL	SOH	STX	ETX	EOT	ENQ	ACK	BELL	BS	H. TAB	LINE FEED	V. TAB	FORM OUT	RETURN	SO	SI
		X	Z_1	DLE	DC1	DC2	DC3	DC4	NAK	SYNC	ETB	CAN	EM	SUB	ESC	FS	GS	RS	US
	X		Z_2	SPACE	!	"	#	$	%	&	'	(	)	*	+	,	—	·	/
	X	X	Z_3	0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?
X			Z_4	@	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
X		X	Z_5	P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	↑	←
X	X		Z_6	◄	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
X	X	X	Z_7	p	q	r	s	t	u	v	w	x	y	z	{	|	}	~	RUB OUT

Y_0,X_0 Y_0,X_1 Y_0,X_2 Y_0,X_3 Y_1,X_0 Y_1,X_1 Y_1,X_2 Y_1,X_3 Y_2,X_0 Y_2,X_1 Y_2,X_2 Y_2,X_3 Y_3,X_0 Y_3,X_1 Y_3,X_2 Y_3,X_3

NON-SHIFT CODES

SUB-CODE COMPONENTS

Z			Y		X	
B_7	B_6	B_5	B_4	B_3	B_2	B_1

8th BIT IS PARITY

Z_7 α SHIFTS TO Z_5, CONTROL SHIFTS TO Z_1
Z_6 α SHIFTS TO Z_4, CONTROL SHIFTS TO Z_0
Z_5 α SHIFTS TO Z_7, CONTROL SHIFTS TO Z_1
Z_3 α SHIFTS TO Z_2
Z_2 α SHIFTS TO Z_3

4. Approach to ASCII. Three part subcode defines ASCII characters: Z coordinate includes 3 most significant bits, X and Y each contain 2 less significant bits. Anomaly in ASCII code requires shifting certain keys (in color) in direction opposite to that of major group shift—lower case to upper case. Result requires two additional Z-coordinate lines, Z_2 and Z_5. Special non-shift codes are required for LINE FEED, RETURN, ESCAPE, SPACE, and RUB OUT keys.

with its impedance-transforming FET generates its own assigned portion of the bit pattern. For example, the lower-case characters a to o lie on the Z_6 coordinate line and are represented by the bit pattern 110, the most significant bits. The latter half of the lower case alphabet, p to z, lies on the Z_7 line and has a 111 bit pattern. In the horizontal direction across the chart, the X and Y coordinates advance in simple binary form.

Selection of a particular character requires a combination of the two least significant bit patterns, determined by the X and Y coordinate lines, and the Z bit pattern. For example, the letter g is represented by coordinate line X_3, whose bit pattern is 11, Y_1, whose bit pattern is 01, and Z_6. Therefore, when the g key is depressed, it is identified by the bit pattern $1100111-Z_6Y_1X_3$.

Ideally, such an arrangement should require only three Z-coordinate lines—Z_3, Z_6 and Z_7—in the non-shift mode. But when the ASCII code was developed, certain lower-case symbols were placed on upper-case lines, requiring an inverted shift function to accommodate them. One such inconsistency is the equal-sign

which appears as upper case on the key and lower case in the code format. These anomalies require shifting certain punctuation symbols (shown in color in Fig. 4) in a direction opposite to that for the group shift. Hence, two additional Z-coordinate lines, Z_2 and Z_5, were introduced, making the logic shift function more elaborate than strictly necessary.

The keyboard is organized to use the fewest possible FETs and logic circuitry. Each coordinate line may have from 11 to 16 key targets attached to it. The drain of each FET impedance converter is connected to a set-reset flip-flop—the entry point to external integrated circuit control logic. Whenever a key is depressed, the FETs attached to the excited coordinate lines execute a momentary closure between the drain and source terminals, placing the associated flip-flop in the SET condition. A timer circuit subsequently clears this flip-flop, but so long as it is set it serves as the source of the output signals. The interface between the keyboard and the control logic is at the drain of the FET, which is a low impedance point capable of driving several feet of wire. Each FET is thus associated with a

In key with computers

The keyboard industry, clearly recognizing where its fortune lies, has striven to keep pace with the rapid growth of the digital computer. Contactless keying mechanisms, such as Hall effect, and electromechanical keys, like the dry reed switch, are competing for a place in today's computer input terminal. Encoding circuits are equally diverse, running the gamut from exotic MOS chips to simple diode matrices.

The competition between keyboard manufacturers, if anything, has increased over the past year [*Electronics*, Nov. 10, 1969, p. 145]. Several new comers are off and running in the keyboard derby.

A keyboard designed around a second-order Hall-effect device is being built by Nucleonic Products of Canoga Park, Calif. The active device is a magnetoresistive chip. A magnet moved near the chip changes the chip's resistance from 40 to 200 ohms, causing a transistor in the key to conduct. An integrated circuit trigger built into the key then shapes the output signal and sends it to a diode matrix encoding circuit.

A ferrite toroidal core is the basis of a design by the Licon division of Illinois Tool Works, Chicago. The core is wound with three wires—drive, sense, and interlock—and is permanently mounted in a plastic housing. Two magnets, mounted on the key plunger, saturate the core, preventing the sense wire from responding to an ac signal on the drive wire. When the key is depressed, the magnets move away from the core, which then acts as a transformer, coupling the ac signal. The signal is converted to dc by an external IC and is transmitted to TTL circuitry for encoding.

Unimax Switch of Wallingford, Conn., offers a keyboard with a "flying magnet" key. The key contains two magnets with their poles in opposition. Each opposed pole resets against a metal strip, with a third strip between them. When the key is depressed, the upper magnet's strip is pushed in contact with the center strip, repelling the lower magnet. The lower strip snaps up to contact the middle strip momentarily. When the three strips touch, a signal is transmitted in two parts—a three-bit and a four-bit segment—to flip-flop circuitry for encoding. The lower magnet returns to its original position in 2 milliseconds, drawing the lower strip away and breaking the electrical contact.

A keyboard that looks like a fat plastic card is built by Flex-Key Corp. of Waltham, Mass. Inside the plastic is a printed circuit board covered by a conductive elastomeric membrane. When the key is pushed down, the membrane is deformed, and it contacts the printed wire line beneath it. The key is compatible with DTL, TTL, and MOS logic interfaces.

In other new keyboards, the emphasis is on encoding. One approach that uses MOS technology is featured in a Hall-effect keyboard built by the Micro Switch division of Honeywell Inc. of Freeport, Ill. A large-scale integrated MOS chip containing the equivalent of 5,000 transistors, resistors, diodes, and gates performs all signal coding tasks. The MOS encoding package has an added feature—n-key rollover. The key's pulsed output is set into the encoding chip's memory, allowing keys to be depressed sequentially so data are entered in the proper sequence, regardless of the order of key release.

Another keyboard that features a single-chip LSI/MOS encoding circuit is made by Clare-Pendar of Post Falls, Idaho. Here, a scanning technique searches for a closure of a dry reed switch key. Clock circuitry contained in the chip operates at 50 kilohertz, permitting a scan rate of 20 microseconds. A 2,000 bit read-only memory, also in the chip, generates an output code that is compatible with DTL, TTL, and MOS circuitry.

A different encoding approach is taken by Cherry Electrical Products of Waukegan, Ill. Its scheme includes an eight-stage clocked, ripple-through counter; two 16-channel multiplexers; a 1-of-16 decoder; a monostable multivibrator; and assorted gates. The 1-megahertz clock scans all possible bit combinations every 256 μs. When a coded signal corresponding to a depressed dry reed switch key is sensed, the clock is inhibited, stopping the counter at a particular eight-bit code. The four most significant bits are fed to the multiplexer, where a strobe activates the circuit, while the four least significant bits go into the 1-of-16 decoder. A matrix connection between the multiplexer and the 1-of-16 decoder is established and a one-shot is triggered generating the encoded signal to the logic.

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set-reset flip-flop which deals with the remaining control circuitry at standard IC logic levels—0 V for a binary 0 and +5 V for a binary 1.

While many logic schemes are possible with the electrostatic impulse key, the one shown in Fig. 5 is a good choice. The logic control section ensures that the individual members of the X, Y, and Z groups produce the output bit patterns assigned to them, and adjusts the three most significant bits for alpha and control shifts. The basic key coding is provided by the layout of the printed circuit board which incorporates coordinate assignments made for the individual key targets.

Fundamental to the keyboard is the timing arrangement which clears any one or all of the X, Y, Z flip-flops after an interval of about 3 ms from the moment that one of the flip-flops has been keyed into the SET condition. During this interval, information is available on the 7 outgoing signal lines, and about midway in the interval a 100-microsecond strobe pulse is issued to propagate it from the key flip-flops into the downstream equipment, such as a cathode ray tube display, the input buffer to a computer, or a printer.

Since a valid 7-bit signal from one of the impulse keys is composed of an X component, a Y component, and a Z component, all three must be present before a strobe signal is transmitted from the circuit. To check that this is so, the strobe pulse is logically ANDed with the X, Y, and Z signal components.

If two or more keys are depressed simultaneously, it's easy to detect with the subcode because at least two Xs, or Ys, or Zs are generated. Sensors, in the form of current summing resistors, are wired to the flip-
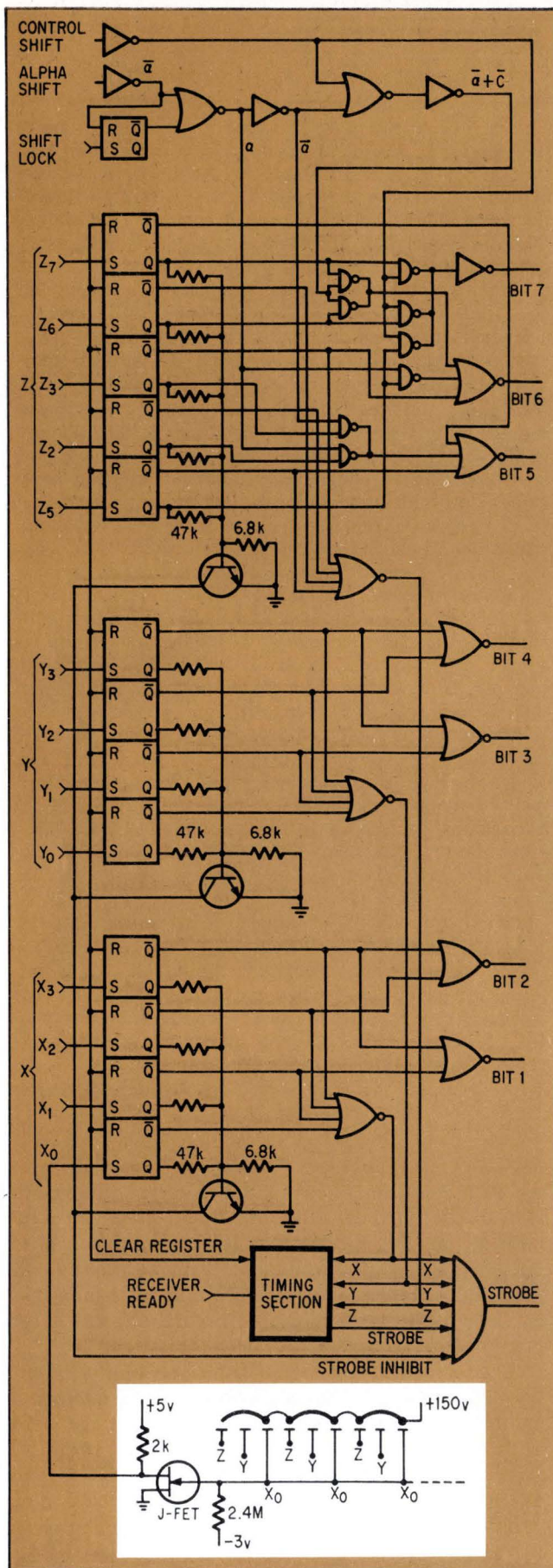
5. Logical approach. Logic scheme utilizes the signals of the impulse keys. Subdivided keys feed into set-reset flip-flops. As an example, keys corresponding to X_0 bits are shown at bottom. When key is struck, an X, Y, and Z flip-flop is set and the proper arrangement of 7 bits is generated. Erroneous data resulting from simultaneous depression of keys are prevented by current summing analog sensors (47 kilohm resistors). If two or more keys are depressed, current developed through resistors turns on transistor, pulling strobe inhibit AND gate input to ground. With strobe inhibited, data stream is blocked.

flops. If more than one key is hit at a time, the current furnished by the affected sensors is sufficient to turn on a transistor which pulls the strobe inhibit line to ground. Since a logic 1 is required on this line for a strobe pulse, no output is generated.

The sensor circuitry is a necessity when the keyboard is transmitting signals to downstream equipment incapable of accepting data at a rate of 200-300 characters per second. In such cases, a receiver-ready signal may be invoked to inhibit the timer cycle until the data can be used. Naturally, the longer the receiver is not ready, the greater the likelihood of multiple key depressions. In such cases, more than one signal will rest in the keyboard register, inhibiting the strobe signal when the receiver ultimately does become ready to accept data.

Of particular importance to keyboard users is the "feel" of the keys. The impulse keyboard, for example, can be made to respond to a light but positive touch because the spring dome feeds back a small impulse to the finger. Furthermore, since the dome spring acts as a snap-action mechanism, such a key can't be teased into producing a partial signal. The polyurethane foam pressure pad has a desirable compression characteristic—it starts out at a low pressure which increases nonlinearly as the key is depressed. Starting pressure is between 50 and 60 grams, and the key operates at a displacement of 0.150 inch and 75 grams; it bottoms at 0.187 inch with a pressure of 80 to 90 grams. The spring recovers its arched position when the applied pressure is reduced to about 65 grams.

An asset of the impulse key is that it need not be raised before a subsequent key is depressed. This increases the reliability of output during burst typing of familiar character groups. Typing speed is therefore limited only by the ability of the operator and the capacity of downstream equipment to accept data.

While the keys in this keyboard require a bias voltage, impulse keys that are completely self-generating, requiring no external bias, could be built with electrets—permanently charged dielectric films—over the target elements. Such electrets are now widely used for biasing condenser microphones.[1] However, the cost of an electret key is more than five times that of a biased key and electret life is not yet established. ☐

Reference
1. P. Murphy and F. Fraim, "Electret Condenser Microphones of High Quality and Reliability," J. Audio Eng. Society, No. 16, p. 450, 1968.