#3

A TIME-GATED AMPLITUDE QUANTIZER FOR NEURAL SIGNALS

An Application to Electric Signals from the Auditory Nervous System

KLAUS PUTTER

LOAN COPY only

TECHNICAL REPORT NO. 275

JANUARY 13, 1954

RESEARCH LABORATORY OF ELECTRONICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS

The Research Laboratory of Electronics is an interdepartmental laboratory of the Department of Electrical Engineering and the Department of Physics.

The research reported in this document was made possible in part by support extended the Massachusetts Institute of Technology, Research Laboratory of Electronics, jointly by the Army Signal Corps, the Navy Department (Office of Naval Research), and the Air Force (Office of Scientific Research, Air Research and Development Command), under Signal Corps Contract DA36-039 sc-100, Project 8-102B-0; Department of the Army Project 3-99-10-022.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
RESEARCH LABORATORY OF ELECTRONICS

Technical Report No. 275 January 13, 1954

A TIME-GATED AMPLITUDE QUANTIZER FOR NEURAL SIGNALS

An Application to Electric Signals from the Auditory Nervous System

Klaus Putter

This report is identical with a thesis submitted to the Department of Electrical Engineering in January, 1954, in partial fulfillment of the requirements for the degree of Master of Science.

Abstract

The conventional analysis of electric signals from the auditory nervous system of anesthetized animals is a laborious and time-consuming task. In general, results are not available until long after completion of the experiment. The time-gated amplitude quantizer (TGAQ) automatically quantizes the amplitudes of preselected portions of the signals and makes possible at least a partial analysis during the course of the experiment. Quantization is achieved by an electromechanical method. The TGAQ is sufficiently flexible to select and quantize signals (responses to single clicks) present at cortical as well as peripheral locations of the auditory nervous system. The TGAQ may be modified to accept responses to stimuli other than single clicks; it may also be modified to give more nearly complete statistical information concerning the data. However, it is primarily a step in the development of equipment that will make the process of analysis of electrophysiological data more and more automatic.

TABLE OF CONTENTS

I. BACKGROUND MATERIAL IN AUDITORY ELECTROPHYSIOLOGY

1.1 INTRODUCTION

The equipment discussed in the following pages has been designed specifically to aid in the first stages of the analysis of data obtained in electrophysiological experiments with acoustic stimuli. Although it is possible to discuss the equipment divorced from this application, the specifications, developmental problems, and tests of the time-gated amplitude quantizer-(TGAQ) will have greater meaning if reference is made to auditory electrophysiology. This introductory section is intended to supply some of the background material required.

1.2 RESPONSES OF SINGLE NEURAL UNITS

Acoustic stimulation of the ear of an anesthetized animal normally evokes in the animal's nervous system electric responses which are superposed on the so-called spontaneous electrical activity that is already present. Responses of individual neural units in the auditory nervous system have been recorded by microelectrodes and have been found to obey the well-known "all-or-none" law. The response is either absent or present; the amplitude of the response presumably does not vary appreciably. The law does not make any statement regarding the instantaneous value of the threshold of the elements; that is, the boundary between the no-response region and the full-response region is not defined. Neither is there any generalization that attempts to relate amplitudes or thresholds of different fibers of a nerve trunk, or that deals with its summated response.

1.3 SUMMATED RESPONSES

The summated response of many neural elements may be recorded with so-called gross (fine-wire) electrodes. In the monopolar recording technique, the "active" electrode is located at a point in whose vicinity activity is to be recorded.* The "indifferent" (reference) electrode is usually located in a neck muscle or at the mouth of the animal and is grounded. The monopolar response reflects, therefore, the electrical activity of all the units occupying the volume between the two electrodes (modified by the inverse-square law), as well as the summation of the individual responses in the immediate vicinity of the active electrode. This is at least a partial cause for the variability of the amplitudes of the summated responses that has been observed.

---

*Specifically, the active electrode is located so that the particular activity of interest is maximized.

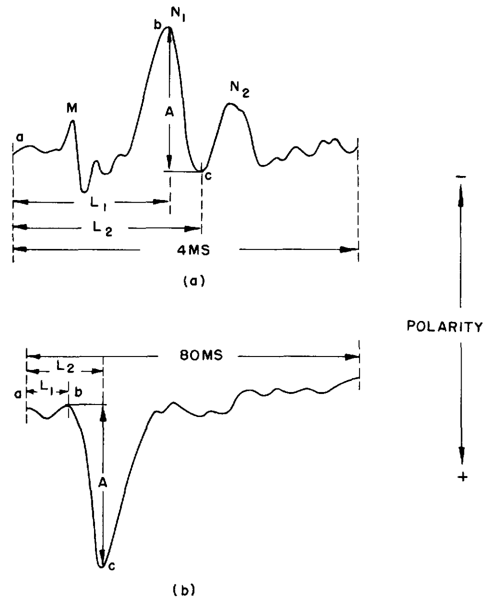


Fig. 1
Sample responses to single intense clicks illustrating some important response parameters.

1.4 RESPONSES TO CLICKS

The properties of the summated responses vary, depending on the location of the active electrode and the parameters of the acoustic stimulus. If the stimulus is a "click,"* the responses recorded near the round window of a cat's cochlea and at the auditory cortex of a cat are of the form shown in Figs. 1(a) and 1(b), respectively. The points labeled "a" correspond to the onset of the electric click presented to the transducer, and are generally taken as the time reference for all other portions of the response. "M" is the earliest prominent deflection of the microphonic. Microphonic potentials are generated in the cochlea and provide an electrophysiological monitor of the acoustic stimuli. The first and second neurals (N_1 and N_2, respectively) arise in neural structures near the peripheral end of the auditory nervous system. As the active electrode is moved to higher auditory nervous centers, later, higher-order neurals become more prominent, and at the auditory cortex the response is spread out over a time interval of considerable duration.

1.5 IMPORTANT RESPONSE PARAMETERS

The response parameters which have been of primary interest so far are the peak-to-peak amplitudes (A) of the response recorded at the cortex and of the first neural component, and the latencies, L_1 and L_2, of the peaks involved. (In this and the

---

*A click is a rectangular pulse of the order of 0.1 msec duration transduced by a high quality (PDR-10) earphone.

following chapters, L_1 is referred to as the "response onset latency." For the peripheral response illustrated in Fig. 1(a), this terminology does not correspond to that commonly found in the literature, and is used for convenience only.) Although the latencies decrease as the intensity of the click stimulus is increased, the latencies of responses to clicks of fixed intensity are remarkably constant, particularly at the peripheral level. Therefore, the measurement of the potential difference between two peaks (peak-to-peak amplitude) may be replaced by the measurement of the potential difference between the potential at a constant latency and the potential of the following peak (constant latency-to-peak amplitude), with little loss in accuracy.

The response amplitudes of the neurals are a function of the stimulus intensity. In general, they increase as the intensity of the click stimulus increases. This is especially true for the amplitude of N_1. The amplitudes of the responses to constant clicks, however, are not constant, so that any analysis of the behavior of the response must be of a statistical nature.

1.6 VISUAL ANALYSIS

The nonautomatic ("visual") analysis of the peak-to-peak, or constant latency-to-peak, amplitudes is an extremely laborious process. The responses picked up by the gross electrode are amplified and displayed on the screen of an oscilloscope whose sweep is driven in synchronism with the onset of the electric click. The oscilloscope traces are photographed on film which is developed and observed on a microfilm reader. Each response is then projected on graph paper, and the amplitude deflection of interest is either quantized directly or read as accurately as possible and quantized later.

The results of the quantization process may be arranged in histogram form, and the mean and standard deviation may be calculated. The histogram ("amplitude distribution data") alone, however, is not enough for a complete analysis of the data. It may also be desirable to calculate certain probabilities based on the time sequence of the individual response amplitudes in quantized form ("sequential amplitude data").

1.7 PURPOSE OF TGAQ

The visual quantization and the calculation of the statistical quantities desired normally require a week or more, and quite often reveal – too late – that it would have been desirable to alter the plan of the experiment. The TGAQ is designed to speed up the quantization process and, more important, to make possible a sufficiently complete analysis of the data so that the experimental plan can be changed during the course of the experiment. The experimenter is, therefore, provided with a sufficient amount of "feedback" to enable him to make more efficient use of the limited time during which data is available.

(For detailed information on theories of hearing, the anatomy and the physiology of the auditory nervous system, and the properties of the responses of the auditory nervous system, see the first five references listed in the bibliography.)

II. METHODS OF QUANTIZATION

2.1 MINIMUM TGAQ REQUIREMENTS

The rough minimum specifications for the time-gated amplitude quantizer follow directly from the properties of the cortical and round-window responses to clicks. Referring again to Fig. 1, the peak-to-peak portion of the first neural may be roughly approximated as a half cycle of a 2-kilocycle sine wave with an onset latency of 1.0 msec to 1.5 msec. The peak-to-peak portion of the cortical response may be thought of as a half cycle of a 50-cycle sine wave with an onset latency of 10 msec. The adequacy of these approximations varies with changes in the parameters of the stimulus, but for most round-window data and at least some cortical data the frequencies and latencies mentioned may be taken to be the extremes of the continuum which the TGAQ must be able to accept.

The TGAQ, then, must be synchronized with the apparatus which supplies the stimulus to the subject, in order to have some fixed time reference with respect to the subject's response. The TGAQ must select portions of the response that follow this fixed time reference by 1.0 msec to 10 msec and that have a duration of 0.25* msec to 10 msec. Since both peaks involved in the measurement may vary in their potential with respect to some fixed potential, the TGAQ must either measure both peaks, or clamp the earlier peak to a fixed potential. And, finally, the TGAQ must quantize the potential difference between the two peaks into some arbitrarily chosen number of levels.

The timing circuits of the TGAQ that select the proper portion of the response can be blocked out in a number of ways which differ in the detailed circuitry but which are basically alike. No matter what the design of the over-all system is, the functions to be performed call for a trigger marking the time at which the animal is stimulated, a variable delay, and a gate of variable width. The quantization of the selected signal, however, can be performed by a great variety of methods, and warrants further discussion. The factors which are of importance in selecting or rejecting a given method of quantization are: accuracy, reliability, the length of the time intervals separating the responses, simplicity, the total number of responses which are to be quantized for a fixed stimulus condition, flexibility, and the number of levels of quantization chosen. A further consideration is the type of information desired; that is, the amplitude (in terms of levels) of each individual response (sequential amplitude data) or the histogram of all the responses (amplitude distribution data).

Present research in auditory electrophysiology conducted by the Communications Biophysics group of this Laboratory requires, as a minimum, twenty levels of quantization. The number of responses to a fixed stimulus required is relatively small — rarely

---

*The minimum duration of the response portion of interest, in general, is not a critical value as far as the TGAQ specifications are concerned. See footnote on page 18.

more than one hundred and usually less than twenty. The animal is generally stimulated at constant rates of the order of one per second, and responses are recorded at the rate at which stimuli are delivered. Finally, since the identity of the individual responses is important, quantization results must be available in the form of sequential amplitude data.

2.2 PHOTOGRAPHIC TECHNIQUES

Most quantization schemes developed for nuclear pulse height analyzers (6) either cannot be used for this application or are unnecessarily complex. Photographic techniques which result in an amplitude distribution in terms of light density in a strip of film exposed to oscilloscope traces may be discarded because of the sequential data requirement and because of the comparatively small number of signals.

2.3 SINGLE-CHANNEL PULSE-HEIGHT ANALYZERS

Single-channel pulse-height analyzers may be similarly abandoned. This classification employs amplitude discriminators with associated circuits which count the number of signals that fall into an amplitude level of fixed width but of variable location. The need for relocating the level for each series of measurements multiplies the time required for taking data by the number of levels desired, and the inherent assumption that the signal amplitude spectrum does not change during the period of measurement is a poor one when the source of the signals is an anesthetized animal. In addition, the identity of the individual responses is lost.

2.4 MULTICHANNEL ANALYZERS

Multichannel analyzers, the brute force technique, may be used but involve a prohibitive number of tubes. In the systems described by Van Rennes (6), each level requires a channel consisting of an amplitude discriminator and associated circuits which prevent the channel from registering a count if its upper boundary – the lower boundary of the channel associated with the next higher level – is crossed within a specified time interval after the lower boundary crossing. A somewhat simpler system, also discussed by Van Rennes, replaces the output suppression circuits with an interrogation arrangement. However, even this scheme requires a large tube complement, and like the others it presents the output in a form which is better suited for amplitude distribution data than for sequential data. The same restrictions apply to methods employing beam-deflection tubes with a separate collector for each level.

2.5 THE "KICKSORTER"

An electromechanical "kicksorter" developed by Frank, Frisch, and Scarrott (7) utilizes an electronic billiard cue to shoot metal balls into slots which indicate the amplitude level of the signal driving the cue. The kicksorter requires less involved electronics than most multichannel devices and can be converted to give sequential as well as distribution data. The major objection to the kicksorter is its relatively poor reliability. Ten to twenty percent of a series of constant amplitude input signals is quantized into the two levels adjacent to the correct level.

2.6 AMPLITUDE-TO-TIME CONVERSION AND PULSE CODE MODULATION METHODS

Amplitude-to-time conversion and pulse code modulation (PCM) methods are not applicable to nuclear pulse-height analyzers because the input pulses may be separated by as little as 2 μsec. These methods, however, are extremely useful in the quantization of electrophysiological responses normally separated by time intervals of the order of 1 sec, and probably not less than 0.1 sec in the immediate future.

2.7 AN ELECTRONIC PCM METHOD

R. W. Sears (8) describes an electron beam-deflection tube for pulse-code modulation which uses a quantizing grid, an aperture plate cut in accordance with a binary number pattern, and a collector plate to quantize the vertical deflection of an electron beam into one of 128 possible levels.

2.8 AN ELECTROMECHANICAL PCM METHOD

A second relatively simple scheme which gives the desired information in terms of a binary code is shown schematically in Fig. 2. A three-gang, six-position stepping switch compares the stored-signal amplitude levels to six successive reference voltages through a single diode amplitude discriminator. Each reference voltage is added to or subtracted from the reference voltage in the immediately preceding position, depending on whether or not the discriminator in that position conducted. A signal of 37.5E

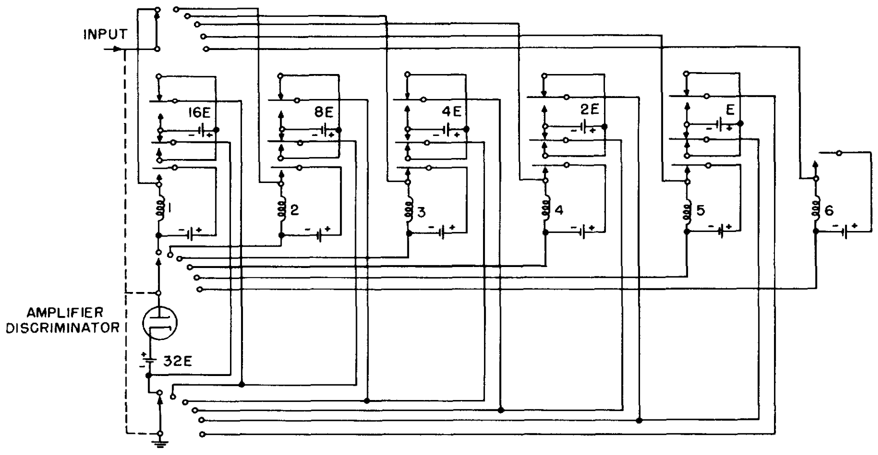


Fig. 2
Binary quantizer schematic.

amplitude, for example, causes relay 1 to close and hold, and is compared to 48 E in position 2. Relay 2 remains open, and the reference in position 3 is 40 E. This process continues until in position 6 only relays 1, 4, and 6 are closed, indicating a signal larger than 32 E + 4 E + E but smaller than 32 E + 4 E + 2 E. This system is limited in speed by the relays and stepping switches and is limited in resolution by the drift of the reference voltages and the difficulty of approximating an ideal diode amplitude discriminator.

2.9 AMPLITUDE-TO-TIME CONVERSION METHODS

The two PCM systems discussed, and others that can be devised, represent a considerable simplification over the brute force multichannel systems, but the necessity for read-out circuits to present the quantization results in sequential form makes straight amplitude-to-time conversion methods preferable. Amplitude distribution data can be obtained quite simply by counting the number of pulses passed by a gated pulse-generator arrangement in which the gate width is a linear function of signal amplitude. For sequential amplitude data, however, the comparison of signal amplitudes to a sawtooth reference leads to a simpler device, and this is the method that has been chosen. The particular system developed is discussed in detail in section III.

III. THE TGAQ SYSTEM

3.1 METHOD OF QUANTIZATION

The basic principle which makes possible the extreme simplicity of the TGAQ is simultaneous amplitude-to-time and amplitude-to-angular position conversion. The amplitude levels of the input signals are transformed into functions of time by comparison to a sawtooth derived from a motor-driven potentiometer. An indicator wheel, driven by the same shaft as the potentiometer, converts time to angular displacement from the position corresponding to the start of the sawtooth. Each signal amplitude, therefore, corresponds to a definite time interval and to a definite angular position — both measured relative to the start of the sawtooth. By graduating the periphery of the indicator wheel into a number of discrete levels, and by briefly pulsing a light source on at the end of the time intervals corresponding to the input amplitudes, the relative amplitudes of the input signals can be read directly from the indicator wheel in terms of illuminated numbers.

3.2 SYNCHRONIZATION OF REFERENCE AND INPUT SIGNALS

The choice of the method of quantization ties down the design of the TGAQ to a large extent; another major choice concerns the synchronization of the reference sawtooth and the animal's response, or of the sawtooth and the stimulus evoking the animal's response; under the assumption of constant response onset latency, the two are equivalent.

In the system developed, synchronization is achieved by triggering the stimulating equipment with a pulse generated electromechanically once every revolution of the continuously driven potentiometer-indicator wheel assembly. This particular method of synchronization avoids the excessive potentiometer wear, the additional circuitry, or the clutch mechanisms concomitant to most methods which would permit the stimulating equipment to operate on an independent time schedule. However, the present design of the TGAQ restricts its use to the analysis of responses evoked by stimuli which may be externally triggered. This inherent limitation of the TGAQ's flexibility is undesirable; it is discussed in greater detail in the final section.

3.3 PHYSICAL DESCRIPTION

The complete time-gated amplitude quantizer is shown in block diagram form in Fig. 3, and schematically in Fig. 4. Figures 5 and 6 are the front and rear views, respectively, of the rack-mounted unit. All negative and positive supply voltages are derived from two Lambda (Model 25) power supplies and five VR tubes. The TGAQ proper occupies the upper two chassis and has a complement of twenty tubes in addition to the VR tubes mentioned. Although the TGAQ can be made considerably more compact than the present model, it is obvious from the photographs that at least two, and probably three, complete units can be mounted on one floor rack. This economy of space and

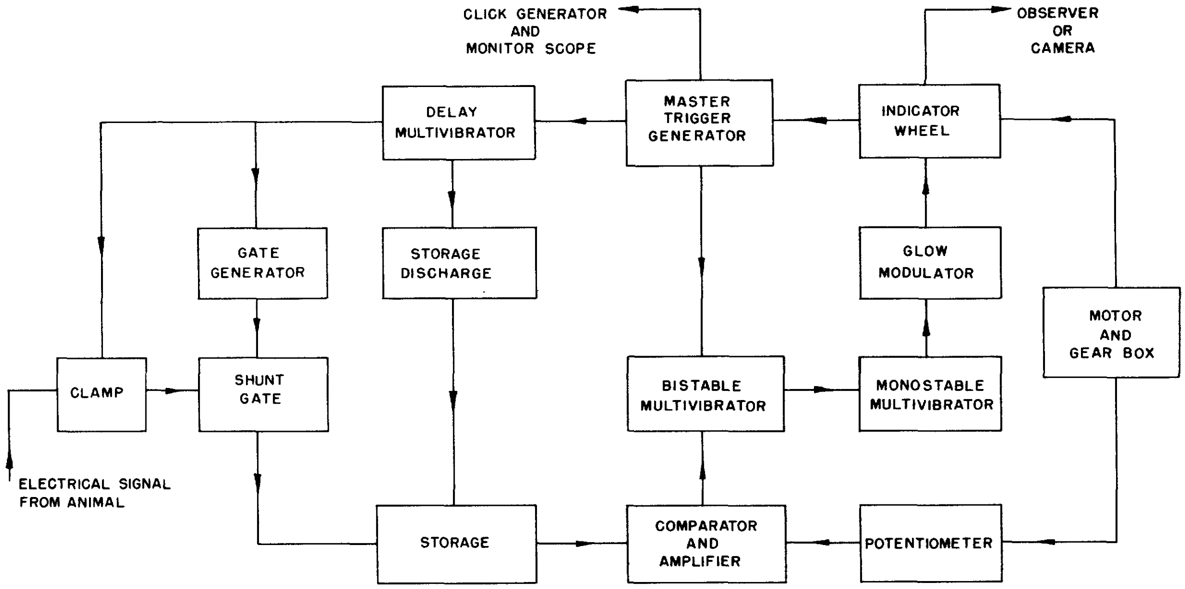


Fig. 3
TGAQ block diagram.

equipment is of considerable importance in the contemplation of the largely automatic analysis of electrophysiological data, and probably represents the principal advantage of the TGAQ over other types of quantizers.

3.4 FUNCTIONAL OPERATION

The functional operation of the TGAQ can be made clear by tracing the signal path along the block diagram (Fig. 3) and by referring to the time schedule (Fig. 7). The "rep rate" control on the front panel, (Fig. 8(a)) is set to drive the potentiometer-indicator wheel assembly at the desired stimulus repetition rate. A metal contact mounted on the indicator wheel trips the master trigger generator once every revolution of the mechanical assembly, and the generated pulse provides the time synchronization for the TGAQ and its associated equipment. External to the TGAQ, the master trigger pulse drives the sweep generator of an oscilloscope monitoring the TGAQ input and determines the repetition rate of the click stimulus generator. In the TGAQ proper, the master trigger pulse trips a delay multivibrator of variable output width. The trailing edge of the delay pulse triggers a gate generator, which closes a shunt gate, and the delay pulse itself is used to activate a circuit which clamps the instantaneous input signal to ground. With the aid of the monitoring scope, the width of the delay pulse is adjusted to release the clamp and close the shunt gate at the time at which the earlier peak of the desired peak-to-peak measurement occurs; this point corresponds to point b on Fig. 1. The width of the gate pulse is then set to hold the shunt gate closed long enough to allow the second peak of the signal excursion of interest to pass into storage through a unilateral charge path, but short enough to shunt subsequent higher

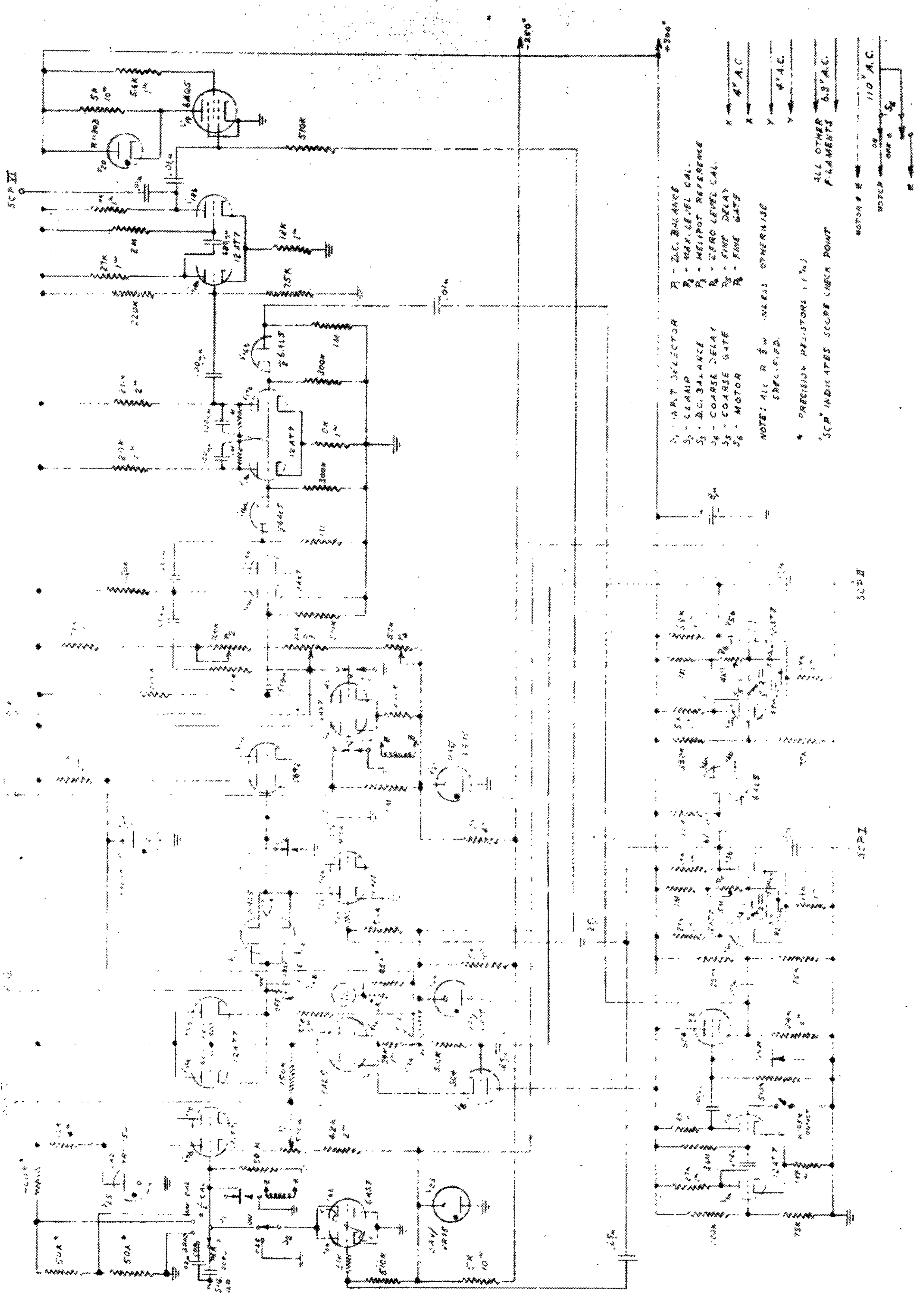


Fig. 4
Complete TGAQ schematic.

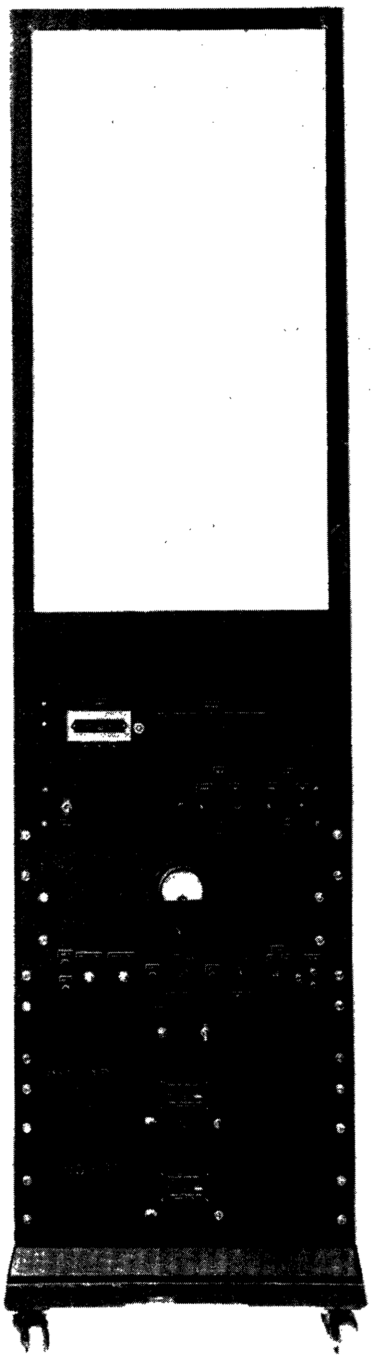


Fig. 5
TGAQ front view.

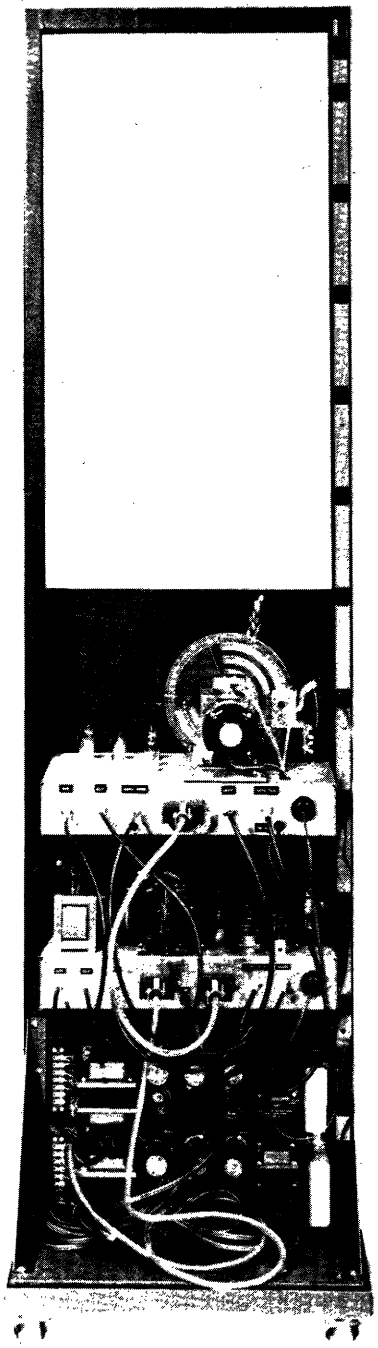


Fig. 6
TGAQ rear view.

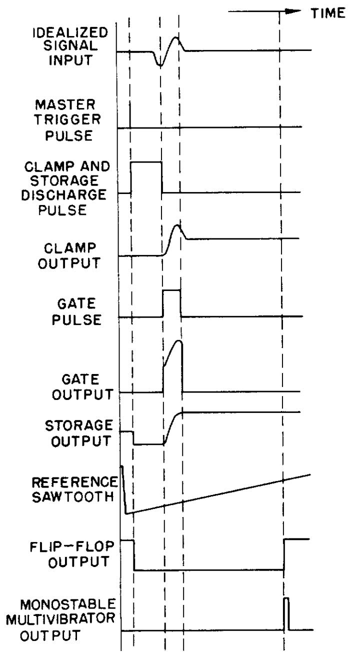


Fig. 7
TGAQ time schedule.

peaks which may occur. The output of storage, then, is proportional to the peak-to-peak amplitude of the response portion selected (A in Fig. 1), and this value is compared to the mechanically generated sawtooth in a double triode comparator. When the two comparator inputs are approximately equal, the output signal flips the following bistable multivibrator which delivers a sharp positive trigger pulse to the monostable multivibrator controlling the light flash duration of the glow modulator. In accordance with the simultaneous amplitude-to-time and amplitude-to-angular position conversion mentioned earlier, the light flash illuminates the indicator wheel number which corresponds to the amplitude of the stored signal.

The next master trigger pulse resets the bistable multivibrator and initiates the next stimulus, scope sweep, and delay pulse. The delay pulse, as before, activates the signal clamp circuit and also a storage discharge circuit. The trailing edge of the delay pulse triggers the next gate pulse, and the cycle repeats.

3.5 NOMINAL SPECIFICATIONS

The illuminated numbers on the indicator wheel may be read by an observer or photographed, depending on the stimulus repetition rate. On the present model, the mechanical assembly is capable of operating at nominal repetition rates of 10, 5, 2, 1, 1/2, 1/3, and 1/5 per second. The signal portion of interest may lag the stimulus by from 0.5 msec to 10 msec, and may have a duration of 10 msec or less.[*] The number of levels of quantization may be either 20, 30, or 40 with an accuracy of ± 1 level.[**] The highest acceptable signal transient, without loss of accuracy, is a 2-kc sinusoid, and the driving amplifier should be capable of delivering 60 volts with a maximum internal impedance of 500 ohms.

The figures given above represent the nominal specifications of the present model of the TGAQ. The following four sections discuss the individual circuits in detail and indicate which specifications can be extended for particular applications.

---

[*] See footnote on page 18.

[**] Since the output is in discrete form, the accuracy cannot be better than ± 1 level, irrespective of the number of levels. Effectively, accuracy may be increased by maintaining the error value of ± 1 level and increasing the number of levels.

IV. THE MECHANICAL ASSEMBLY AND THE TIMING CIRCUITS

4.1 PARTS OF THE MECHANICAL ASSEMBLY

Figure 8 shows the top and front views of the chassis housing the mechanical assembly and the timing circuits. The mechanical assembly is relatively simple and consists of a 1/50 hp, 1725-rpm, split-phase motor; a gear box; a single-turn, 360 mechanical degrees Helipot; the indicator wheel; and an adjustable mounting bracket for the glow modulator tube.

4.2 GEAR BOX

The gear box is modeled after the chart drive for the Offner dynograph (Type 506/501A, manufactured by Offner Electronics, Inc., Chicago, Illinois) and represents a particularly neat and compact way of getting a large number of different input-to-output ratios. The arrangement employs two shafts supporting two floating gear trains related in space so that they drive each other at progressively slower speeds. The output speed is selected from the upper gear train by a ratcheted sliding gear controlled by a gear shift brought out through the center of the indicator wheel and moved parallel to the axis of the gear train.

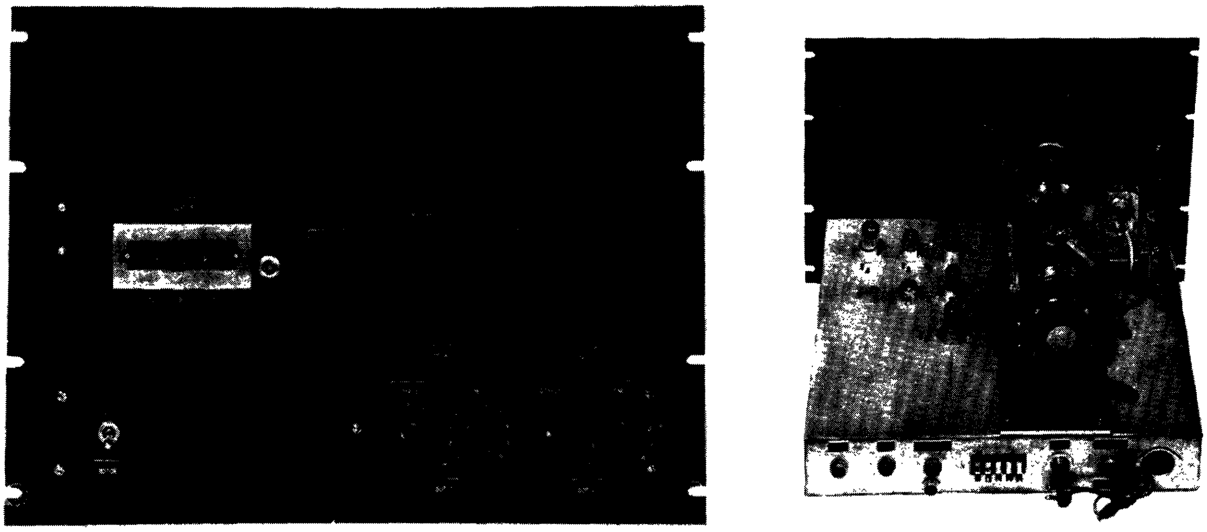
4.3 INDICATOR WHEEL

The indicator wheel is shown in detail in Fig. 9. The wheel itself is bakelite with three circular concentric slots cut through a 270° sector. The slotted sector is covered by a single brass number plate mounted flush with the front of the wheel. Each slot exposes a different set of numbers on the brass plate to the glow modulator light source mounted directly behind the wheel in a nine o'clock position. By opening the proper window on the front panel (Fig. 8(a)), and by sliding the glow modulator to the mounting bracket position directly behind the corresponding slot, forty, thirty, or twenty levels of quantization may be chosen. The center line of each slot is located so that the individual numbers in all three slots are the same size.

The quadrant of the wheel which is unslotted is necessary to allow sufficient time after the occurrence of the master trigger pulse to select and store the desired portion of the signal before the actual quantization takes place. At the fastest nominal rate of 10 rps, the time allowed is one-fourth of 100 msec, or 25 msec. This time period is sufficient to give the maximum delay and gate width specified, and still leave 5 msec leeway for the initial phasing adjustment of the potentiometer and the indicator wheel.

4.4 PHASING ADJUSTMENT

The Helipot used has 360° mechanically but only 357° electrically, so that at the highest speed (10 rps) the sawtooth generated has a break, or retrace, of slightly less than 1 msec. In terms of angular position of the wheel, this break must occur between



(a) Front view.

(b) Top view.

Fig. 8
Chassis housing mechanical assembly and timing circuits.

Fig. 9
Indicator wheel (front view).

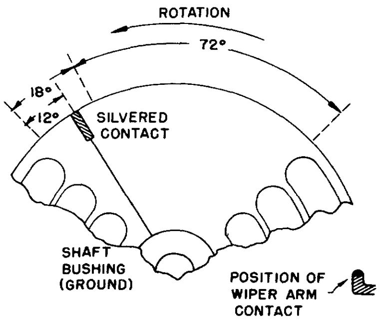


Fig. 10
Partial sketch of indicator wheel (rear view).

the position corresponding to the last level in the comparison process and the position corresponding to the onset of the master trigger pulse. Since the sawtooth reference used has a positive slope, since there is no inversion of the stored signal, since the rotation of the wheel is clockwise, and since 20 msec must be allowed for signal selection, the previous statement means that the break must occur in the 18° sector of the unslotted portion immediately following the highest numbers in each number set. As shown in Fig. 10, the silvered copper contact which initiates the master trigger pulse is mounted flush with the rear of the wheel following the highest numbers in each set by 12°. This still allows better than 3 msec for phasing, and provides more than the maximum 20 msec specified for signal selection and storage.

The phasing adjustment is made once when the potentiometer is first installed or when it is replaced, and requires the use of an oscilloscope whose sweep is triggered by the master trigger pulse. After approximate phasing by relative positioning of the gear-box output gear and the potentiometer shaft gear, the sawtooth, as viewed on the scope face, is adjusted with the fine shaft positioning control (Fig. 8(b)) until the break just precedes the start of the sweep.

If the break were to follow the start of the sweep – that is, follow the master trigger pulse, the bistable multivibrator triggering the output stages would be activated before the start of the comparison process, and would be unable to accept the pulse indicating the amplitude level of the stored signal. If the break were to precede the master trigger by more than the dead time allowed on the unslotted portion of the indicator wheel following the highest numbers in each set, the stored signals corresponding to the higher levels would be compared to the break voltages and would give no output at all.

4.5 MOTOR AND MOUNTING BRACKET

The motor driving the gear box is not subject to any strict requirements. Constant speed is necessary only in so far as it is desirable to maintain a reasonably constant stimulus repetition rate. From the standpoint of quantization accuracy, speed variations are not a factor, for the indicator wheel and the potentiometer providing the reference voltage are driven from the same shaft.

The motor can be used in conjunction with a thyratron speed control to provide continuously variable repetition rates. However, for this particular application, it is preferable to have the discrete but accurately repeatable speeds provided by the gear box. Two unwelcome by-products of the gear box used at present are somewhat noisy operation and awkward speeds. (The actual speeds, as measured by electronically counting a large number of master trigger pulses and dividing by time, are 10.44, 5.86, 2.35, 1.32, 0.74, 0.42, and 0.23 rps.) Neither of these defects is critical, and both can be rectified by the use of helical, instead of spur, gears and by keeping closer tolerances on the gears used.

The adjustable mounting bracket for the glow modulator tube is a simple aluminum bracket slotted to facilitate movement of the tube for independent illumination of any one of the number sets on the indicator wheel.

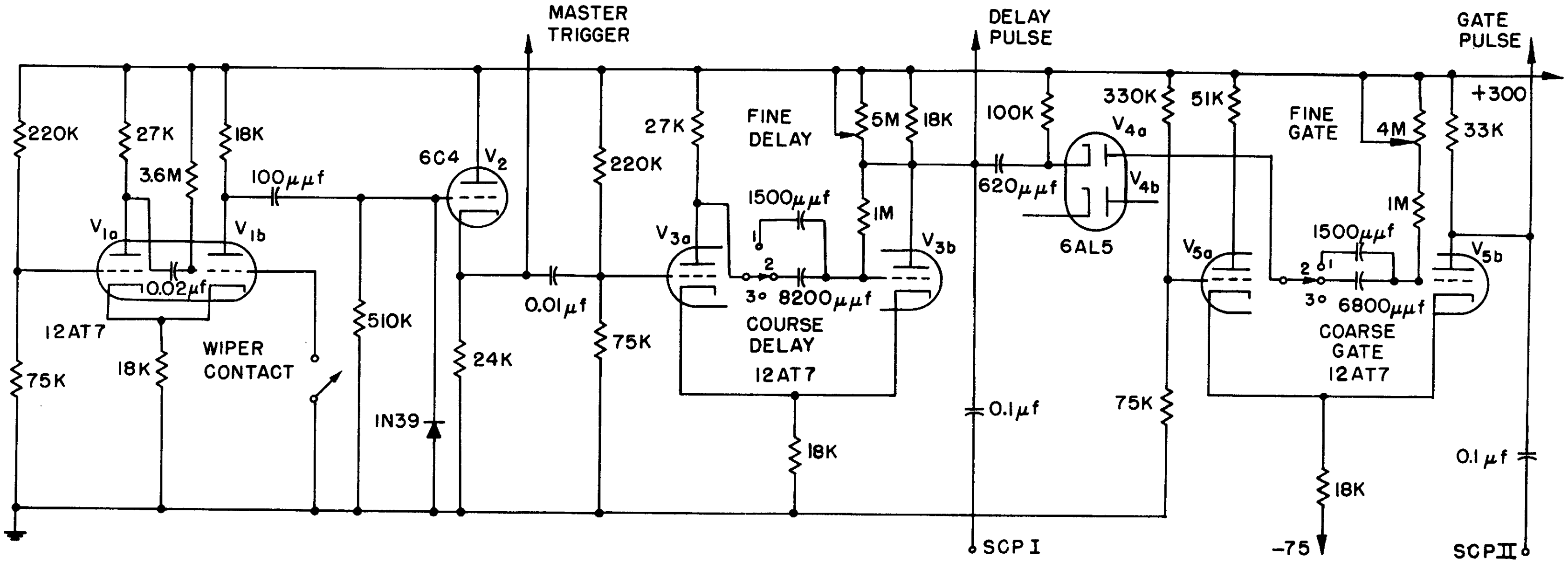


Fig. 11
TGAQ timing circuits.

(a) Master trigger pulse.

(b) Master trigger pulse, expanded sweep.

(c) Delay pulse.

(d) Gate pulse.

Fig. 12

Timing circuit waveforms. All waveforms are triggered by the master trigger pulse and represent less than a full TGAQ cycle. Sweep speeds and TGAQ settings for (a), (c), and (d) are identical. Correct amplitude relations have not necessarily been preserved.

4.6 MASTER TRIGGER PULSE

The electronic portion of the chassis housing the mechanical assembly is relatively conventional and requires only superficial discussion. The circuits shown schematically in Fig. 11 generate the pulses required for the operation of the clamp, gate, and storage discharge circuits. V_1 is a positive grid return monostable multivibrator with V_{1b} normally conducting (9). The brush contact in the grid circuit of V_{1b} is a wiper which, through the contact imbedded in the rear face of the indicator wheel and connected to ground through the gear box housing, grounds the V_{1b} grid once every revolution. The positive pulse generated at the V_{1b} plate is differentiated, and the negative spike is clipped. The positive spike is brought out through the cathode follower V_2 as the master trigger pulse referred to previously. Since the multivibrator period is longer than the time interval for which the brush contact is closed, even at the slowest speed, the effects of contact noise are eliminated, and the trigger is a reliable spike of about 100-volts peak amplitude, 100 μsec base width, and 500-ohms source impedance at the pulse peak.

4.7 DELAY MULTIVIBRATOR AND GATE GENERATOR

The delay multivibrator V_3 and gate generator V_5 are also monostable positive grid return multivibrators. The master trigger pulse initiates the delay pulse at the grid of V_{3a}, and the trailing edge of the delay pulse triggers the grid of V_{5a} through the coupling diode V_4. Both the delay multivibrator and the gate generator provide pulses whose width is continuously variable over more than the specified range of 0.5 msec* to 10 msec in two overlapping steps. The cathode resistor of the gate generator has been returned to a negative supply voltage in order to provide a sufficiently large output pulse to hold the shunt gate closed even if the selected response portion is of high amplitude. No particular effort has been made to obtain flat-topped pulses, the minimum possible jitter, or the shortest possible rise and fall times. Although for the present specifications of the TGAQ these possible causes of error are negligible, they should be kept in mind if the accuracy (number of levels) is to be materially increased.

The delay and gate pulses are brought out at pin jacks on the front panel in "scope check points" in order to facilitate the checking of normal or troublesome operation. In addition, of course, both pulses, as well as the master trigger pulse, are cabled to the other chassis for the performance of the functions mentioned in section 3 and discussed in detail in section 5.

Pertinent timing circuit waveforms are shown in Fig. 12.

---

*The minimum width of the gate pulse is critical only if a high-frequency response is immediately followed by an undesired signal of higher amplitude. An unused position on the "coarse gate width" switch allows the gate pulse width to be further decreased, if desired.

V. THE INPUT, SIGNAL SELECTION, AND STORAGE CIRCUITS

5.1 INTRODUCTION

The clamp (V_6), input cathode follower (V_7), shunt gate (V_8 and V_9), buffer cathode follower (V_{10}), charging diode (V_{11}), storage discharge (V_{12}), and storage (V_{13}) comprise the input, signal selection, and storage circuits shown schematically in Fig. 13. The top and front views of the chassis housing these circuits, and those discussed in the next section, are shown in Fig. 14.

5.2 CLAMP CIRCUIT

The clamping and holding of high-frequency signals is difficult to perform accurately, but by taking advantage of the comparatively narrow frequency distribution of any given set of response portions at any given location the circuit requirements can be considerably eased. The present model of the TGAQ clamps (and holds) low-frequency signals from the auditory cortex on a "cortical" range – 50 cycles to 400 cycles, and clamps (and holds for shorter intervals) high-frequency signals from or near the round window on a "peripheral" range – 400 cycles to 2000 cycles. A detailed consideration of the circuit requires an RC transient study. This study is made in Appendix I. Qualitatively, when the clamp is on, the input capacity charges approximately to the instantaneous value of the input signal. When the clamp is released (point b in Fig. 1), V_6 cuts off, and the capacitor charge does not appreciably change until the following positive peak has passed into storage.

The purpose of the V_6 grid current limiting resistor is to reduce loading of the delay multivibrator. The relay contact automatically grounds the V_7 grid when the motor is turned off, so that the grid-to-ground impedance is not kept continuously high for long periods of time. The heater of V_6 is operated at four volts in order to raise the back resistance of V_6 from a few hundred megohms to several thousand megohms. The forward resistance is not appreciably affected.

It may be worth noting also that the grounded-plate section of the clamp tube may conduct for large negative signals even though the clamp is presumably off. There is no need to correct for this effect because the clamp-off operation is important only during the gate interval, when the input signal of interest is always positive. When negative peaks are of interest, the signal must be inverted prior to the TGAQ input.

5.3 INPUT CATHODE FOLLOWER, GATE, AND BUFFER CATHODE FOLLOWER

The input cathode follower (V_7) is designed to be a single-stage compromise between the low-tube currents and voltages required for low-grid current (about 10^{-9} amps) and the high currents required for a sufficiently low output impedance to make the nonlinear loading effects of the following shunt gate negligible. This loading effect is also one of the factors determining the minimum value of the 150-kilohm dropping resistor. The

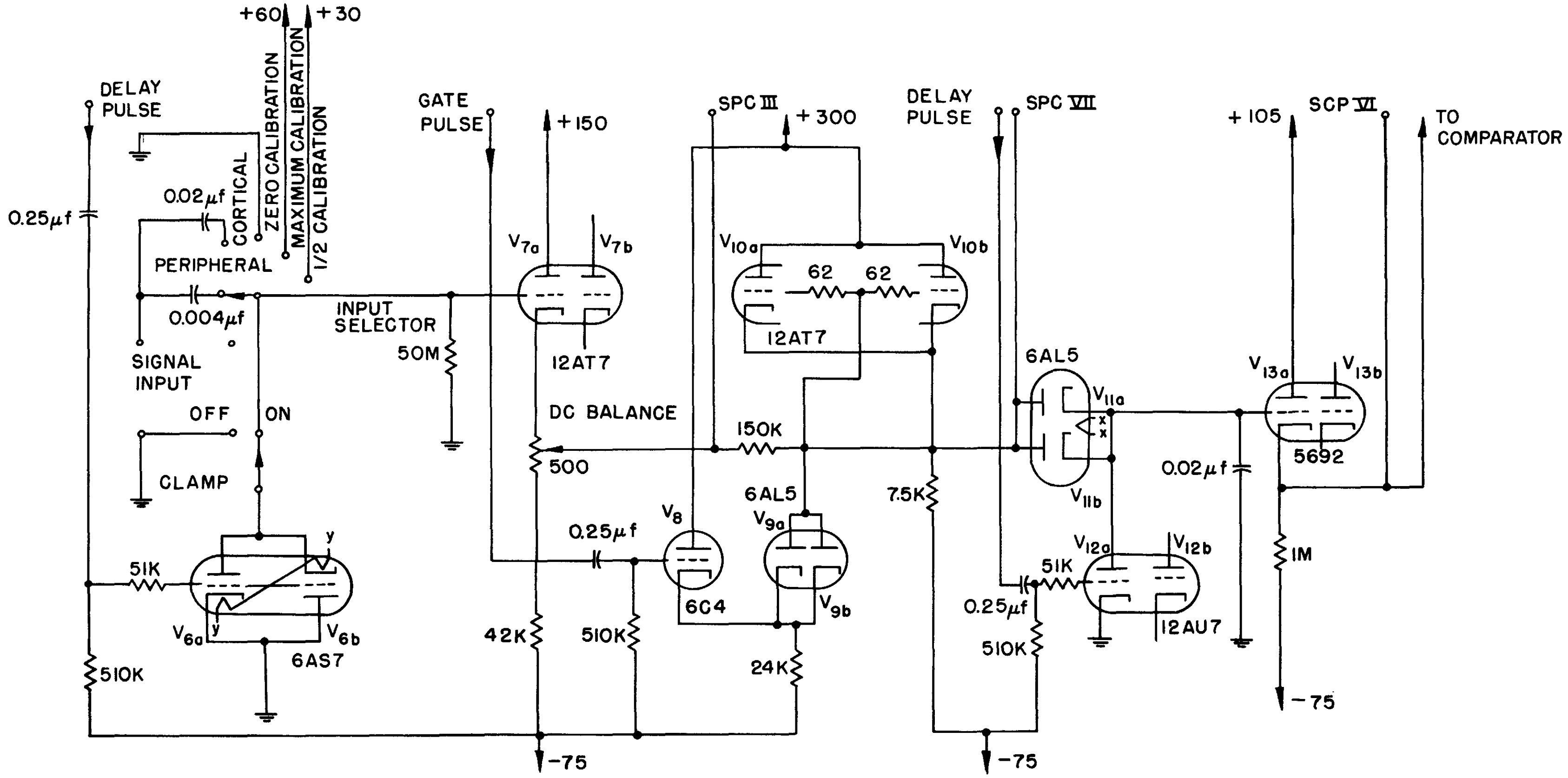
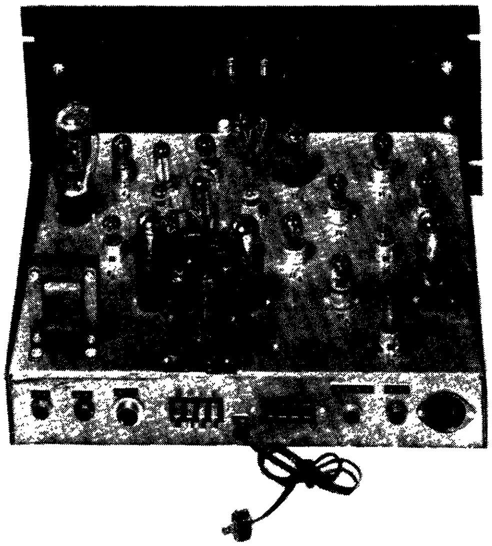


Fig. 13

TGAQ input, signal selection, and storage circuits.

(a) Front view.



(b) Top view.

Fig. 14

Chassis housing input, signal selection, storage, comparator, and output circuits.

(a) Clamp to negative peak of 500 cycle sinusoidal input.

(b) Corresponding delay pulse.

(c) Gate output for 500 cycle sinusoidal input of approximately the same phase relation to the master trigger pulse as in (a).

(d) Corresponding gate pulse.

(e) Storage output for dc input.

(f) Storage output for input as in (a).

Fig. 15

Waveforms: input, signal selection, and storage circuits. All traces represent less than a full TGAQ cycle and are triggered by the master trigger pulse. Sweep speeds and TGAQ settings for all waveforms are identical. Correct amplitude relations have not necessarily been preserved.

second factor is the operation of the gate itself. In the absence of the gate pulse, the 150- and 24-kilohm resistors form a voltage divider which, through the buffer cathode follower V_{10}, applies a negative plate to cathode voltage to the charging diode V_{11}. Since the diode capacity is negligible in comparison with the storage capacity itself, the signal rejection is virtually complete.

The cathode follower V_8 increases the 6:1 ratio of the physical resistances, but its primary function is to reduce loading of the gate generator. The gate pulse introduced through V_8 cuts off the shunt diode and allows the previously clamped signal to pass into storage through the low-impedance path provided by the buffer cathode follower and the charging diode. Two sections of a 12AT7 operating at a combined transconductance of about 8000 μmho are inclined to oscillate at high frequencies, and the grid resistors act as parasitic suppressors.

5.4 STORAGE AND STORAGE DISCHARGE

A complete transient analysis of the signal path from the output of the input cathode follower to the output of the storage circuit is complex and unnecessary. A piecewise analysis of considerable detail is given in Appendix II.

The 5692 (the premium version of the 6SN7) has been chosen mainly for its long life and high stability, although it also appears to have slightly less grid current than the 6SN7. As in the clamp circuit, a relay contact automatically grounds the storage-tube grid when the motor is turned off and the grid is not grounded periodically through the normal action of the discharge tube V_{12}. V_{12} is driven directly from the delay multivibrator, and the grid current limiting resistor is inserted to reduce loading.

Although V_{12} discharges the storage capacitor-to-ground potential, the buffer cathode follower output for shorted TGAQ input is about +6 volts. The signal applied to the storage circuit (see the waveforms in Fig. 15) therefore "rides" on a dc pedestal. This pedestal shifts the operating region of the charging diode sufficiently to eliminate nonlinearities due to contact potential and the slight curvature of the diode characteristic near the break. The pedestal itself is compensated for by the calibration adjustments on the following comparator.*

The output of the storage circuit is fed directly to one of the comparator inputs. It and the following circuits are discussed in the next section.

---

*The introduction of the pedestal and the negligible drift of the input stages eliminate the need for the "dc balance" control and the associated metering circuit. The original purpose of this circuit was to provide some means of zeroing the buffer cathode follower output for zero TGAQ input. At present the circuit balances at about +6 volts (for zero TGAQ input) and serves only as an indicator of possible troubles in the input stages.

VI. THE COMPARATOR AND THE OUTPUT CIRCUITS

6.1 INTRODUCTION

Volume 19 of the M.I.T. Radiation Laboratory Series (10) describes a large number of circuits which perform amplitude comparison. Of these circuits, the double triode comparator is particularly suited for the TGAQ application. It does not require pulse transformers, which would limit its application to "fast" waveforms; and, more important, it provides a convenient means of blocking the storage discharge pulse from the output circuits.

6.2 CALIBRATION PROCEDURE

As mentioned in section III, the relative timing of the sawtooth applied to the V_{14b} grid (see Fig. 16, the schematic for the comparator and the output circuits) and the master trigger pulse is adjusted mechanically so that the sawtooth break, or retrace, just precedes the master trigger. With the input selector switch set at "zero cal" (ground), the "zero level calibrate" potentiometer is adjusted until the top of the number 1 just appears at the bottom of the window on the front panel. With the input selector switch set at "max cal" (about 60 volts positive), the "maximum level calibrate" potentiometer is adjusted until the bottom of the number 40 just disappears at the top of the window on the front panel. These two adjustments, repeated alternately until both numbers are properly located, set the TGAQ input at 1.5 volts per level and keep the grid-to-cathode potential of V_{14b} sufficiently negative during the prequantizing portion of the TGAQ cycle to hold V_{14b} cut off. The storage output is less positive during the storage discharge pulse (delay pulse) than it is for zero TGAQ input, so that the delay time is limited by the requirement that V_{14b} remain cut off during the entire prequantizing interval, even at the highest speed.

6.3 COMPARATOR ANALYSIS

The action of the comparator, then, is as follows. The circuits preceding V_{14} apply a voltage E, corresponding to the peak-to-peak amplitude I of the selected signal, to the grid of the cathode follower V_{14a}. The common cathode has the potential

$$e_K = E + |e_{ca}|$$

where the grid-to-cathode voltage of V_{14a}

$$e_{ca} = f(E)$$

V_{14b} begins to conduct when the reference voltage

$$e_r = e_K - |e_{cob}|$$

where the V_{14b} grid-to-cathode voltage at the point of conduction

$$e_{cob} = g(E_{bb} - e_K)$$

and hence

$$e_{cob} = h(E)$$

Now if

$$e_{cob} = e_{ca} = \text{constant over the applicable range of } E$$

then the amplitude-to-time conversion of I is of the form

$$T = t_o + kI, \quad \text{for any one speed}$$

where t_o is the prequantizing interval, $1/k$ is proportional to the slope of the reference voltage, I is the peak-to-peak amplitude of the selected input signal ($0 \leqslant I \leqslant 60\,V$).

List of symbols

I	peak-to-peak amplitude of selected input signal
E	storage output value corresponding to I
e_K	common cathode potential of V_{14}
e_{ca}	grid-to-cathode voltage of V_{14a}
e_r	instantaneous reference voltage
e_{cob}	grid-to-cathode voltage of V_{14b} at the point of conduction
E_{bb}	supply voltage
T	time interval corresponding to I
t_o	prequantizing interval of TGAQ cycle
k	constant

The data in Appendix III show the assumption of a constant difference between the conduction point bias of V_{14b} and the operating bias of V_{14a} to be about as good as the measuring techniques used. Qualitatively, it is apparent that both potentials decrease slightly as E increases.

Since there is no additional coupling between the two sections of V_{14} (other than tube capacities), the circuit is not a bistable device, and there is no switching action as there would be in a multivibrator. The initial conduction of V_{14b} does, however, close a feedback loop through V_{15}, and guarantees the application of a reasonably sharp switching waveform to the bistable multivibrator V_{17}, even at slow speeds. Although the oscillations continue for the remainder of the TGAQ cycle, V_{17} and its coupling diode V_{16a} block all but the first positive wavefront.

The sawtooth retrace cuts V_{14b} off and breaks the feedback loop. The next master trigger pulse resets V_{17} through the coupling diode V_{16b}, and the cycle repeats. The relay contacts, shown in Fig. 4, automatically ground both grids of V_{14} when the motor is turned off. Both sections of V_{14} then conduct, and there is no danger of shifts in the

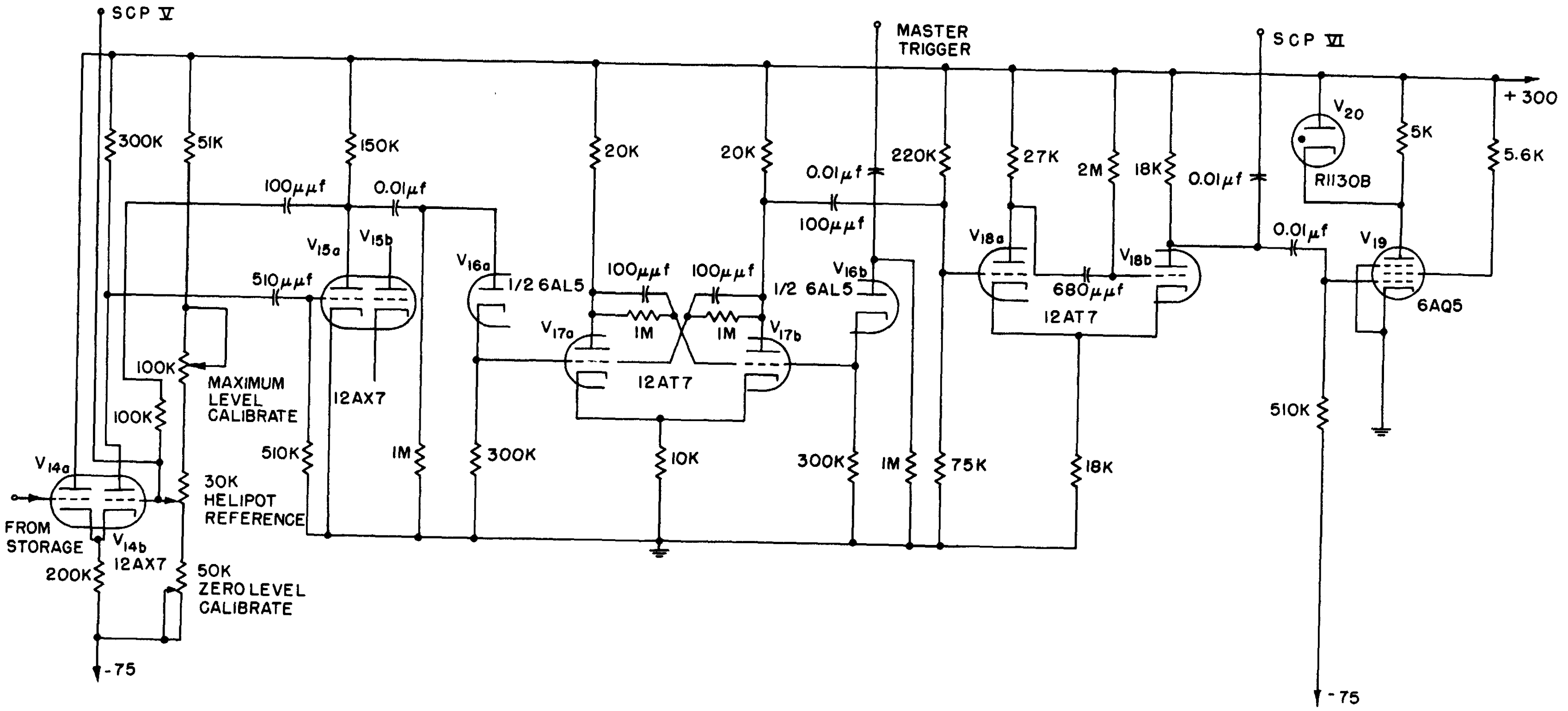


Fig. 16
TGAQ comparator and output circuits.

(a) V_{14b} grid for dc input of 1/2 cal; oscillations indicate start of conduction of V_{14b}.

(b) V_{14b} plate under the same input conditions.

(c) V_{17} output under the same input conditions.

(d) V_{18} output under the same input conditions; break in base line indicates position of pulse.

(e) V_{18} output, expanded sweep.

(f) V_{19} plate, expanded sweep.

Fig. 17

Waveforms, comparator and output circuits. Traces (a) through (d) are triggered by the master trigger pulse and represent more than a full TGAQ cycle; (e) and (f) triggered by waveforms shown. Sweep speeds and TGAQ settings for (a) through (d) are identical. Correct amplitude relations have not necessarily been preserved.

characteristics of either section of the tube because of prolonged cutoff conditions.

6.4 OUTPUT CIRCUITS

The remaining stages are conventional. V_{17} triggers the monostable multivibrator V_{18} which determines the light flash duration. V_{19} supplies the power to V_{20}, the actual light source. V_{20} is a Sylvania 1B59/R1130B cold-cathode glow modulator tube and is designed to give light which is continuous but modulated by an electrical signal. In this application, where V_{20} is either cut off or fully conducting, it exhibits what in the absence of detailed structural tube information must be passed off as some sort of capacitance effect. In order to operate reliably, the opaque coating on the glass shell must be grounded. The reliability is impaired only if the ambient light level is low. Normal room lighting – or even a flashlight beam aimed at the front of the tube – apparently aids the ionization process sufficiently to give completely reliable operation. Since the TGAQ is normally used in a darkened experimental chamber, the ground connection must be made.

Pertinent comparator and output circuit waveforms in response to a dc TGAQ input of 30 volts ("1/2 cal" on the input selector switch) are shown in Fig. 17.

VII. APPLICATIONS, LIMITATIONS, AND ALTERATIONS

7.1 INTRODUCTION

The opening section made clear that the TGAQ was designed for a specific application – sequential data reduction for electrophysiological experimentation in audition. Since the TGAQ is a special-purpose device, a discussion of applications other than the one intended is of questionable value. However, the TGAQ does have properties that make a few general comments worthwhile.

7.2 GENERAL APPLICATIONS

The most obvious limitation to general application of the TGAQ is that the significant input must have a low repetition rate. Furthermore, the input should be small sample data and, or, the sequential amplitude data, rather than the amplitude distribution data, should be of interest. If the input signals meet these requirements, the TGAQ may be used in two major ways. First, it may be used as a peak-to-peak or, with the clamp switched off, as an average-to-peak measuring device of a signal having a constant time relation to the master trigger pulse. Second, it may be used as an "interval peak" sampling device of a continuous signal of unspecified time relation to the master trigger pulse, where "interval peak" is defined as the peak value occurring during an interval and measured with respect to the value at the start of the interval or with respect to the average value of the signal.

For any of the preceding types of measurement, the TGAQ may be used in its present form to quantize linearly. In addition, by replacing the linear potentiometer and number plate, a large number of different types of quantization processes may be performed with the equipment otherwise unchanged. Logarithmic quantization is the most obvious example.

7.3 ELECTROPHYSIOLOGICAL APPLICATION

The TGAQ may be used with other electrophysiological signals similar to those from the auditory nervous system. This application was implied in the discussions of the opening sections.

7.4 FACTORS LIMITING TGAQ SPECIFICATIONS

Most of the TGAQ specifications are victims of the simplicity and flexibility of the equipment, and it may be worthwhile to summarize the factors limiting each specification. This summary discusses the limitations resulting from the design of the system, not the limitations caused by the hardware values chosen. The actual specifications of the present model of the TGAQ are given in parentheses for easy reference and do not necessarily represent the limits imposed by the factors mentioned in the discussion.

Maximum repetition rate (10.44 rps): At least 21 msec must be allowed for phasing and signal selection. This requirement is independent of speed so that the ultimate limitation on the maximum speed is the minimum time and the minimum percentage of one potentiometer revolution required for accurate quantization. Potentiometer life is a second consideration.

Minimum repetition rate (0.23 rps): For high input signal levels, the TGAQ must hold the stored levels for almost a complete TGAQ cycle. The minimum speed is, therefore, limited by the storage-leakage time constant. The time constant can be considerably increased by using cascaded storage circuits, or the error resulting from leakage can be reduced by reversing the comparison process so that the high levels are compared first; the volts per level are independent of amplitude while leakage is a percentage of amplitude.

Maximum delay (10 msec): The delay time cannot exceed a certain percentage of the precomparison interval of the TGAQ cycle or V_{14b} will not be held nonconducting during the discharge of the storage circuit. This requirement limits the delay time at the highest speed.

Minimum delay (0.5 msec): Since the delay pulse is also the storage-discharge pulse, the minimum delay is limited by the storage-discharge time constant. For signals having a narrow amplitude distribution, the delay can be decreased; complete discharge is not necessary.

Maximum gate width ("cortical" range, 10 msec; "peripheral" range, 2.0 msec): Gate width is limited by the leakage time constant of the clamp circuit. It can be increased by an electrometer tube in the input circuit.

Minimum gate width (0.5 msec): This specification is not limited by any TGAQ parameters.

Maximum acceptable frequency (2 kc/sec): The upper frequency response is limited by the time constants of the clamp circuit, the storage circuit, and the stray lag at the input of the buffer cathode follower. These time constants can be decreased, and the frequency response extended, by adding an electrometer tube in the input stage and by cascading storage circuits.

Minimum acceptable frequency (50 cps): The low-frequency limit is determined by the maximum gate width.

Accuracy (± 1 level, at 40 levels or less): The accuracy, of course, determines the maximum number of levels of quantization. In the present model, drift is negligible compared with 1.5 volts per level at 40 levels, and the comparator accuracy itself is not the only limiting factor. Accuracy is also limited by frequency, repetition rate, and input signal amplitude for the reasons already discussed. Quantizing into less than the maximum number of levels just means that the full accuracy is not being utilized, and any number less than or equal to the maximum may be chosen.

It is worth noting that the accuracy is also affected by the conditions under which the TGAQ is calibrated. For example, loss of accuracy caused by leakage of the storage capacitor may be partially compensated for by calibrating at low repetition rates. In general, however, it is inadvisable to use the calibration adjustments as a means of compensating for errors; the application of the TGAQ and the evaluation of the accuracy of its output are made unduly complex.

7.5 DISADVANTAGES AND SUGGESTED ALTERATIONS (LATENCY VARIATIONS)

Section I mentioned that the latency of the responses which the TGAQ is designed to quantize is a function of the intensity of the stimulus. In the present model of the TGAQ, therefore, it is necessary to reset the width of the delay (clamp) pulse every time the intensity of the stimulus is changed.

The necessity of making these settings can be eliminated by externally triggering the clamp off and the gate on at the time at which the response has reached the first peak of the desired peak-to-peak measurement.* Revision of the TGAQ to accept such an external trigger is relatively simple (although the development of the device which will provide it is not) and has the additional advantage of eliminating the requirement of a constant response onset latency entirely.

7.6 DISADVANTAGES AND SUGGESTED ALTERATIONS (STIMULI OTHER THAN SINGLE CLICKS)

A factor which severely limits the flexibility of the TGAQ is the stimulating equipment's time dependence on the TGAQ cycle. When the stimulus is a single pulse at a constant repetition rate, the triggering of the stimulating equipment presents no problem. However, it is sometimes desirable to analyze the response to the second pulse of a pair of pulses separated by variable time intervals, or to a tone burst of constant initial phase, or, possibly, to pulses presented at random rates. It will probably also be desirable to analyze data recorded on tape.

Although the present model of the TGAQ may be adapted to meet some of these applications, particularly at low repetition rates, the flexibility of the system would be greatly increased by allowing the stimulating equipment to trigger the TGAQ, rather than vice versa. External triggering of the TGAQ is permissible if the mechanical assembly can be equipped with a mechanism which, when pulsed, drives the load through one complete revolution; supposedly such mechanisms are commercially available. Electronically, the system would be unchanged except that the master trigger pulse is replaced by a trigger from the stimulating equipment, and that following the storage of the desired signal, an activating pulse must be supplied to the mechanical assembly.

The revised system would have the additional advantage of eliminating the need for the motor and gear box and of making storage time independent of stimulus repetition rate. As a result, storage leakage could be made a negligible source of error. The

---

*A companion instrument of the TGAQ which will measure this time and provide the trigger is now being developed by A. K. Hooks of the Communications Biophysics group of the Laboratory.

present system is, of course, capable of operating at greater speeds than the revised system would be. However, much of the present experimental work is concerned with responses spearated by time intervals of the order of one second or more.

7.7 DISADVANTAGES AND SUGGESTED ALTERATIONS (TYPE OF OUTPUT)

The output of the present model of the TGAQ is not in a form which may be fed directly into other equipment whose function it would be to compute the statistical quantities desired. However, the TGAQ can probably be revised to calculate some of these quantities itself.

The number of responses can obviously be counted by counting master trigger pulses, whether the master trigger pulse is provided by the TGAQ itself or by the stimulating equipment, as described in the preceding section. With the master trigger pulse provided externally, the number of possible methods of summing the quantized response amplitudes depends to a large extent on the speed and acceleration characteristics of the device driving the indicator wheel.

One possible method would use a second indicator wheel driven by the same shaft and having narrow slits instead of numbers. These slits would be illuminated by a second glow modulator tube which is turned on by the master trigger pulse and off by the output of the bistable multivibrator. The output of a photoelectric cell located on the other side of the wheel would be a "pulse count" equal to the level of the quantized signal.

This pulse count could be fed directly into a counter and, together with the count of the number of master trigger pulses, would give sufficient information for the calculation of the mean amplitude of the quantized responses.

Since a pulse train is a form of output which readily drives other equipment, the pulse count could be fed into computing equipment for the calculation of the standard deviation, variance, and whatever other terms are desired. It may also be possible to use this output to drive a printer which automatically records the quantized amplitude of the signal and thus eliminates the need for the original indicator wheel entirely.

7.8 MULTIPLE CHANNEL TGAQ

Quite often it is desirable to quantize two or more amplitude deflections of the same response. For this application, the response could be recorded on tape and applied to the TGAQ input for two or more separate quantizations, or the response could be fed directly to two or more TGAQs.

For responses separated by long time intervals, it is possible to use only one TGAQ with two or more "timing" and "input, signal selection, and storage" circuits. Each response, then, would correspond to two or more TGAQ cycles, and the output of each storage circuit would be applied to the comparator during separate successive cycles.

If two or more different response portions of different responses are to be quantized, the multiple channel TGAQ becomes particularly simple. Only the timing circuits need to be duplicated and a switching circuit added to apply the master trigger pulse to the desired delay multivibrator and gate generator.

7.9 CONCLUSION

The present model of the TGAQ has already been used in a number of experiments dealing with peripheral responses. A comparison of visual quantization and TGAQ quantization for one such experiment is given in Appendix IV.

Further experimentation, using the TGAQ as an aid in analysis, will determine what modifications of the present model are desirable (in addition to those already discussed) and will suggest means of making the analysis process more completely automatic.

Acknowledgment

The author is particularly indebted to Prof. W. A. Rosenblith. Also, he would like to thank Prof. A. B. Van Rennes of the Electrical Engineering Department; H. G. Weiss, F. R. Naka, and R. P. Sallen, all of Lincoln Laboratory; and R. M. Brown and the other members of the Communications Biophysics group of the Research Laboratory of Electronics.

References

1. S. S. Stevens (editor), Handbook of Experimental Psychology (John Wiley and Sons, New York, 1951) pp. 1075-1143.
2. S. S. Stevens and H. Davis, Hearing: Its Psychology and Physiology (John Wiley and Sons, New York, 1938).
3. E. G. Wever, Theory of Hearing (John Wiley and Sons, New York, 1949).
4. W. A. Rosenblith and M. R. Rosenzweig, Electrical responses to acoustic clicks; influence of electrode location in cats, J. Acoust. Soc. Am. 23, 583-588 (1951).
5. W. A. Rosenblith, Auditory masking and fatigue, J. Acoust. Soc. Am. 22, 792-800 (1950).
6. A. B. Van Rennes, Pulse amplitude analysis in nuclear research, Nucleonics, pp. 20-27, 22-28, 32-38, 50-56, July 1952 through October 1952.
7. S. G. F. Frank, O. R. Frisch, and G. G. Scarrott, A mechanical kick-sorter (pulse size analyzer), Phil. Mag. 42, 603-611 (1951).
8. R. W. Sears, Electron beam deflection tube for pulse code modulation, Bell System Tech. J. 27, 44-57 (1948).
9. M.I.T. Radar School Staff, Principles of Radar, second edition (McGraw-Hill Book Company, Inc., New York, 1946) pp. 2.53-2.58.
10. B. Chance et al, Waveforms, Vol. 19, M.I.T. Radiation Laboratory Series (McGraw-Hill Book Company, Inc., New York, 1949) pp. 335-363.
11. H. Levick, Sampling circuit for an electronic analog correlator, ScM. Thesis, Department of Electrical Engineering, M.I.T., 1951.

APPENDIX I

Although the equivalent clamp circuit of Fig. 18 does not represent the true physical conditions, in which S_2 is short-circuited and S_1 closes at some time preceding $t = 0$ of Part I, its use does not make the results obtained inapplicable to the physical circuit.

PART I

The differential equation for $0 \leqslant \omega t \leqslant \pi/2$ is

$$iR + q/c = E \sin(\omega t + \lambda) - E_o$$

where $R = R_1 + R_2$, $\lambda = \pi$, and $E_o = Q_o/C$.

Using any of the standard methods of solution, we obtain

$$e_c = \frac{-E}{\omega Z C} \cos(\omega t + \pi - \theta) - E \sin\theta \cos(\pi - \theta) \exp\left(\frac{-t}{RC}\right) + E_o \exp\left(\frac{-t}{RC}\right)$$

at $\omega t = \pi/2$

$$e_c = -E \sin^2\theta + E \sin\theta \cos\theta \exp\left(\frac{-t}{RC}\right) + E_o \exp\left(\frac{-t}{RC}\right)$$

Assuming the exponential terms to be negligible

$$\frac{e_c}{E} \approx -\sin^2\theta$$

For any desired clamp accuracy, then, θ may be found and $|\tan\theta| = 1/\omega RC$ gives the relationship between R and C.

The 500 ohms per section of the 6AS7G (this analysis assumes that the tube resistance is constant) is about the least that can be achieved with a single stage, and significant decreases require unreasonable peak power capabilities of the driving amplifier.

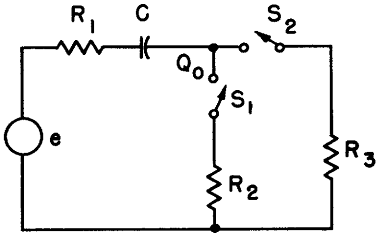


Fig. 18
Equivalent clamp circuit.

$e = E \sin(\omega t + \lambda)$
R_1 = source impedance
R_2 = forward clamp tube impedance
R_3 = clamp off input impedance
Q_o = charge on C at $t = 0$

Part I: $\lambda = \pi$, S_2 open; S_1 closes at $t = 0$ and opens at $\omega t = \pi/2$.
Part II: $\lambda = 3\pi/2$, S_1 open; S_2 closes at $t = 0$, remains closed.

Knowing R_2 and the source impedance, the minimum value of C is readily determined.

For the peripheral responses (2 kc/sec), the clamp capacity is 0.004 µf, and $e_c/E = -0.997$, so that the clamp error is 0.3 percent.

For this calculation, R has been taken to be 1 kilohm in order to allow for the source impedance.

For these circuit values, $t/RC = 31.25$, and the assumption of negligible exponential terms is justified.

PART II

When the clamp is released, the physical circuit acts as if S_1 and S_2 in the equivalent circuit were, respectively, opened and closed. If the clamp release time is taken as $t = 0$, the new transient problem has the same differential equation as before, but with

$$R = R_1 + R_3 \approx R_3$$

$$\lambda = \frac{3\pi}{2}$$

and $E_o = e_c/E$ found in the preceding part.

At $\omega t = \pi$ ($3\pi/2$, using the time reference of Part I), we have

$$e_c = E \sin^2 \theta \left[1 + \exp\left(\frac{-t}{RC}\right)\right] + \frac{e_c}{E} \exp\left(\frac{-t}{RC}\right)$$

We determined C in Part I, and the maximum R_3 is limited by the grid current of the input stage. In this case, R_3 is 50 megohms, so that the lowest frequency for which the charge on C is held accurately for a half period (the required gate width) is 400 cycles (0.625 percent leakage).

Since the clamp error is a direct function of frequency, while the hold error is an inverse function of frequency, the two errors calculated above represent the worst conditions for each and do not add directly.

The remaining portion of the frequency band (50 cycles to 400 cycles) is covered by the "cortical" position of the input selector switch. Here C = 0.02 µf; the clamp error is 0.3 percent at 400 cycles; and the hold error is 0.625 percent at 80 cycles and 1.0 percent at 50 cycles.

The frequency range of 50 cycles to 2 kc/sec is, therefore, covered in two ranges with a maximum total clamp error of slightly over 1 percent. This bandwidth restriction is permissible, since response portions of interest at any given location have a fairly narrow frequency distribution.

These errors are referred to input signal amplitude. The maximum total clamp error is 40 percent of one level (for 40 levels).

APPENDIX II

Like the clamp circuit, the storage circuit requires a short charge time constant and a long discharge time constant. Since the gate width is normally adjusted to be slightly more than a half period of the input waveform, the storage circuit has sufficient time to charge to $E \sin \theta$, rather than $E \sin^2 \theta$ as in Appendix I. Thus for a charge time constant, $\tau = 5\ \mu\text{sec}$, the maximum charge error is 0.2 percent at 2 kc/sec.

The 5 μsec time constant is physically and theoretically correct (the charge path impedance has a design value of 250 ohms) but difficult to measure. With a constant dc input to the TGAQ (clamp off), the idealized action of the gate pulse following the storage discharge pulse is to apply a dc step to the storage circuit. Actually, the considerable input capacity of the buffer cathode follower and the high gate impedance interpose an additional lag. The voltage applied to storage, therefore, is an exponential, and the corresponding differential equation is

$$iR + \frac{1}{C} \int i dt = E \left[1 - \exp\left(\frac{-t}{T}\right) \right]$$

where T is the time constant of the applied exponential. The solution in terms of e_c/E is

$$\frac{e_c}{E} = \frac{T}{T - \tau} \left[1 - \exp\left(\frac{-t}{T}\right) \right] - \frac{\tau}{T - \tau} \left[1 - \exp\left(\frac{-t}{\tau}\right) \right]$$

Measurement of e_c/E can be made on a scope presentation of the storage output waveform, and T and τ, knowing their approximate relative sizes from the circuit values, can be determined by trial and error.

A transient analysis taking into account all the physical conditions is still more complex and hardly justified. Therefore, the charge path impedance is assumed to be constant, the other stray and tube capacities are neglected, the gate pulse is assumed to have a leading edge of infinite slope, and the six-volt pedestal of the waveform applied to the storage circuit is neglected.

The over-all maximum charge error from clamp output to storage output at 2 kc/sec may be taken as 0.4 percent: 0.2 percent, storage; 0.1 percent, stray lag; 0.1 percent, neglected factors.

The discharge time constant for storage must be sufficiently long to hold the charge accurately for 4.35 sec, one complete TGAQ cycle at the slowest speed. Although V_{13} has been designed for the lowest currents and voltages possible with a sixty-volt grid swing, the grid current of V_{13} is the most important factor affecting the charge leakage.

With the grid held at 0 volts for five minutes and then charged to +60 volts, the charge leakage causes a voltage change

$\Delta e = -0.2$ volt in approximately 4.4 sec because of the electron current. With the grid held at + 60 volts for five minutes and then discharged to 0 volt, the charge leakage causes a voltage change

$\Delta e = +0.2$ volt in approximately 4.4 sec

because of ion current. With the grid held for five minutes at the same potential as that at which leakage is measured

$|\Delta e| < 0.1$ volt in approximately 4.4 sec.

This difference in leakage is probably caused by capacitor "soaking." The measurements which gave 0.2 volt change represent unusually severe conditions, and this value may be taken as the greatest possible error.

The leakage caused by the back resistance of the 12AU7, the leakage resistance of the capacitor, the back resistance of the 6AL5, and the cathode-to-ground resistance (through the filament transformer) of the 6AL5 are practically negligible; the equivalent resistance of all four is on the order of 10^{11} - 10^{12} ohms. In order to achieve this order of magnitude of leakage resistance, the heater voltage of the 6AL5 had to be decreased to approximately four volts, and the 6AL5 filament had to be isolated from ground through an air core filament transformer, but no refinements were necessary to obtain a high plate-to-cathode resistance on the cut-off 12AU7. This fact is somewhat at odds with the 2600 megohms obtained in Levick's measurements (11); however, Levick used a voltage-divider measuring technique in which the internal impedance of a standard VTVM (about 10 megohms) formed one part of the divider, and the back resistance of the 12AU7 the other. The results given here are based on stop-watch measurements of the decay time of the charge. The voltage indicator was the low scale of a VTVM (with bucking batteries) metering the output of V_{13}. Leakage caused by grid current was corrected for by comparing the readings with and without the 12AU7 and the 6AL5 connected in the circuit. Although some error is concomitant to the manual switching of leads and the stop-watch measurements, the order of magnitude of the results may be accepted as correct.

The errors on charge and hold, then, under the worst possible operating conditions (0.2 percent charge error in terms of input voltage, 0.2 volt hold error at any given voltage) represent a total error, referred to one level, of no more than 21.5 percent of one level at 40 levels and probably less. The two errors are different functions of frequency, repetition rate, signal amplitude, and other parameters, and do not combine in the simple fashion assumed above.

The 12AU7 forward resistance, as measured by observing the discharge portion of the storage-output waveform during TGAQ operation with a constant dc input, is approximately 7.5 kilohms. The forward resistance of the clamp circuit (500 ohms) was measured similarly, by substituting the 6AS7 for the 12AU7.

APPENDIX III

Since a theoretical evaluation of the linearity of the double triode comparator must be based on experimentally derived curves, the linearity was measured directly with the test setup (Fig. 19). The calibration potentiometers were adjusted to give a reference voltage swing of about 75 volts. (In actual operation, the required swing is only about 50 volts, so that this test is stricter than necessary.) The input to the V_{14a} grid was then adjusted to center all numbers from 1 to 40 in the front panel window; each input value was read with the Leeds and Northrup voltage box and potentiometer, type K-1. Readings were repeatable to 0.1 volt; the TGAQ speed was 0.74 rps.

The deviation of the input voltages from a calculated linear input is plotted in Fig. 20 as a function of output level. There are several sign crossovers, and the largest single deviation from linearity is approximately 0.2 volt. This error is of the same order of magnitude as the measurement error and includes number wheel and reference sawtooth nonlinearities as well as the actual comparator nonlinearity. The accuracy limit imposed by the double triode comparator itself is therefore not established by this measurment technique; but it can safely be said that the comparator and output stages of the TGAQ introduce no more than 0.3 volt error, or 20 percent of one level at 40 levels. If the number of levels is to be materially increased, readings should be repeated for a number of tubes, taking more points over the pertinent voltage range.

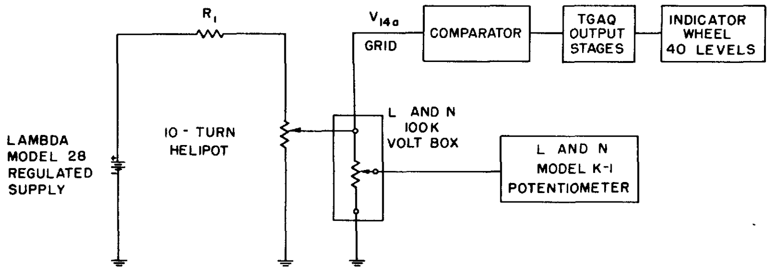


Fig. 19
Comparator linearity measurement setup.

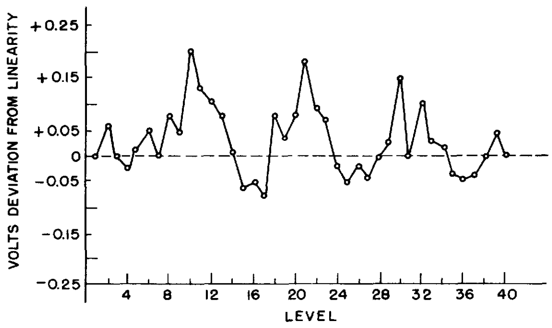


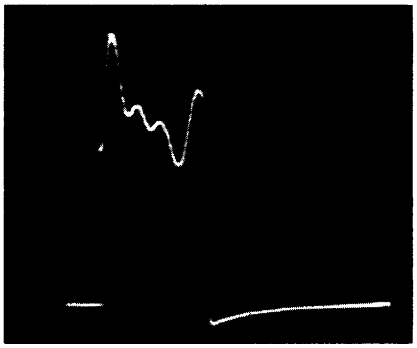
Fig. 20
Comparator linearity graph.

APPENDIX IV

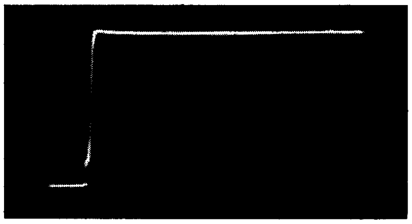
One hundred round-window responses to single intense clicks presented once every 1.35 sec were photographed for visual quantization of N_1, which was simultaneously quantized by the TGAQ. The film data were read as accurately as possible on a microfilm reader. These data were normalized to the TGAQ data by setting up a scale for the visually read responses having the same number of equal interval levels as the highest level appearing on the TGAQ during the run. The width of these intervals was the ratio of the magnitude of the largest visually read response to the TGAQ quantized level for that response plus or minus one half level. The choice of where in that interval (from minus one half to plus one half level) this maximum response fell was arbitrarily made to provide the best agreement between the two series of quantized data.

(a) TGAQ input.

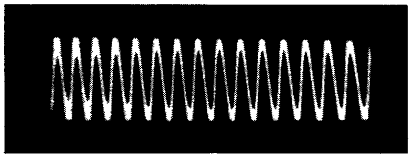
(b) Clamp output.



(c) Gate output.



(d) Storage output.



(e) 5 kc/sec sweep calibration.

Fig. 21

TGAQ waveforms under actual experimental conditions. Quantization of first neural evoked by single intense clicks. Electrode located at round window of cat's cochlea. All traces shown represent less than a complete TGAQ cycle, are triggered by the master trigger pulse, and are taken with identical TGAQ and oscilloscope settings on successive inputs.

Table I

COMPARISON OF TGAQ AND VISUALLY QUANTIZED DATA

	TGAQ	Visual	Error (0.69 = 1 TGAQ level)
1.	33	34	+0.1
2.	31	31	
3.	33	33	
4.	31	32	+0.3
5.	33	33	
6.	32	32	
7.	32	32	
8.	31	31	
9.	31	31	
10.	32	32	
11.	33	32	-0.1
12.	31	31	
13.	34	34	
14.	31	31	
15.	32	32-3	
16.	32	32	
17.	33	33	
18.	33	33	
19.	33	33	
20.	31	31	
21.	32	32	
22.	30	31	+0.1
23.	31	31-2	
24.	32	32	
25.	32	32	
26.	32	32	
27.	32	32	
28.	32	33	+0.1
29.	32	32	
30.	32	32	
31.	33	32	-0.1
32.	33	32-3	
33.	33	33	
34.	32	32	
35.	32	32	
36.	31	31-2	
37.	32	33	+0.1
38.	31	31	
39.	33	33-4	
40.	33	33	
41.	31	32	+0.3
42.	32	32	
43.	33	32	-0.1
44.	31	31	
45.	33	32	-0.3
46.	32	32-3	
47.	32	32	
48.	31	31-2	
49.	33	33	
50.	33	33	
51.	33	34	+0.1
52.	33	33	
53.	32	32	
54.	32	33	+0.1
55.	32	32	
56.	32	32	
57.	31	31-2	
58.	33	32-3	
59.	32	32-3	
60.	30	30-1	
61.	32	32	
62.	33	32	-0.1
63.	33	33	
64.	32	32	
65.	31	31	
66.	31	31	
67.	34	33	-0.1
68.	32	33	+0.2
69.	35	35	
70.	31	31	
71.	32	32	
72.	32	32	
73.	32	31	-0.1
74.	32	32	
75.	33	34	+0.1
76.	31	31-2	
77.	33	33-4	
78.	32	32	
79.	32	33	+0.1
80.	33	33	
81.	32	32	
82.	32	32-3	
83.	33	33	
84.	31	31	
85.	32	32	
86.	31	32	+0.1

TGAQ mean	32.09
Visual mean (junction readings taken low)	32.12
Visual mean (junction readings taken high)	32.28

The comparison of the two series of data is sequentially shown in Table I along with the error, if any, by which the visually quantized data exceed the limits of the level in which the response was placed by the TGAQ (one level = 0.69 visually quantized units). Of the 100 original responses, 14 could not be read because of noise pickup.

Of the 86 readable responses, the TGAQ placed 53 in the "correct" level; 14 are boundary cases at the junction of two levels, 12 are one level too low, and 7 are one level too high. However, in the case of the "incorrectly" quantized responses, all errors are less than one level, and in this particular case the mean of the visually quantized data is actually slightly less close to the mean of the unquantized data than the mean of the TGAQ data is.

This experiment cannot be taken as a reliable test of the TGAQ accuracy, but it does indicate that TGAQ and visual quantization do not differ by more than one level, as specified; and, more important, it shows that (for peripheral data at least) the original assumption of constant response onset latency is sufficiently good to yield reasonably reliable measurements.

Critical TGAQ waveforms taken during this experiment are shown in Fig. 21.