NASA CR 71058

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THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Digital
Liquid Level Transducer

Report No. EDC 1-65-33

by
Fred M. Welsh

June 1965

Harry W. Mergler
Professor of Engineering
Principal Investigator
Ns G 36-60

Digital
Systems
Laboratory

ABSTRACT

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A technique for accurate, absolute binary measurement of liquid level by ultrasonic means is developed; and a measurement instrument is designed, fabricated, and evaluated. The Digital Liquid Level Transducer differs from the conventional ultrasonic depth indicating system in that two time encoding measurements form the raw data to a limited purpose digital computer which corrects the measurement for sound velocity, density, and temperature changes of the liquid. The second time measurement over a known distance is used to eliminate the velocity of sound from the equation which defines the level of the liquid. The concept is also shown to eliminate the periodic calibration of the counting frequency of the time encoding.

The instrument, which was logically implemented on an existing pilot-plant, has a resolution of $\pm$ 0.1% for its 2 ft. water depth range over temperatures of 40 to 100°F, and operates at a counting frequency of 4.95 Mc./sec. The extension of the compensated measurement concept to greater depths for the same full range resolution is discussed in detail.

Author

ACKNOWLEDGMENT

I wish to express appreciation to those who have aided my educational progress:

To Dr. H. W. Mergler for providing counseling during the graduate program and insight into this study,

To S. Daniels, D. Gawlowicz, and D. Vlack with whom technical interchange occurred,

To my parents for providing the educational foundation, and

To my wife, Jan, for her understanding and patience throughout the university career.

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The representative symbols of the various digital and analog devices which form the Digital Liquid Level Transducer are presented in Appendix A. Also presented there are the circuit schematics and their operational characteristics.

CHAPTER I

DIGITAL MEASUREMENT OF LIQUID LEVEL

Measurement and Control

Quantitative information describing the condition of a physical system is provided solely by the measurement of its physical properties. One or all of the measurements of pressure, temperature, composition, and quantity may be required to satisfactorily describe a system. For control purposes, this adequate description is studied in order to judiciously adjust the manipulated variables such that regulation of the system according to some desired criterion is accomplished. In short, the finesse of control of a system or industrial process rests both on the accurate description of the process through measurement methods and on the criterion of control.

An example of the adverse effect of the measurement method on the controlled system performance is any measurement method whose speed of response is large in comparison to the rate of change of the measured variable.[1] Such a measurement method in a feedback control system would reduce the over-all effectiveness of the control. A second example of this adverse effect is the presence of some undesirable feature in the measurement method which cannot be controlled and which produces errors in the measurement. The Bourdon pressure indicator will provide an illustration. Ideally the pressure reading on the scale is linearly related to the pressure over a given range. Yet such an indicator might change its apparent reading of the same pressure if the ambient temperature surrounding the indicator varies over a wide range.

At this point, the designer of the measurement and control equipment for a given process has a number of choices.

1. He can accept the error introduced by the measurement method. This is an obvious solution if the error introduced by such inferior measurement will not adversely affect the over-all control.
2. He can add compensation to the control algorithm in order to compensate for the measurement method. This technique usually involves the sensing of more information about the process.
3. He can strive to improve the measurement method and thereby maintain enough simplicity and generality in the controller to enable its use in a number of applications.

His decision will probably be made on the bases of the control desired, the availability of equipment to satisfy his need, and the cost.

The acquisition and the representation of quantitative information in a digital form is an area in which the designer is faced with the same dilemma. The high degree of accuracy and rapid calculation capability inherent in the digital control device can be hampered by the inaccuracy of the measurement method, by its own time lag, and by some undesirable features in the measurement technique. The measurement of a process liquid level and the conversion of this information into a digital representation is such a measurement and control problem. Measurement methods presently include float operated, pressure, and electronic gages.[2] The first two methods involve the sensing of level by some kinematic means, while the electronic methods incorporate measurement of capacitance, sonar pulses, radiation, and contact and radio-frequency sensing of the surface. The transformation of the measurement into digital data will be considered by the kinematic and the ultrasonic methods. To examine each of these methods is the purpose of the remaining portion of this chapter. Through this examination, the background for the Digital Liquid Level Transducer will be developed.

Sensing by Kinematic Means

The sensing of a liquid level by kinematic means is a method of measurement which involves the movement of a measuring probe. If the level is sensed directly, such a method uses "...floats with their associated linkages and inaccuracies,...".[3] The indirect method might use a pressure sensitive device to convert the hydrostatic head to a linear motion which is proportional to liquid level. The conversion of the linear motion into a digital quantity by the use of a brush or optical encoder completes the measurement requirement. Thus the physical-digital interface is bridged by some movement altering and/or amplifying kinematic system.

The advantages of such a linkage system are as follows:

1. Low cost,
2. Relative simplicity,
3. Ability to function without outside sources of power, and
4. Capability of responding to level changes and not to changes in surface wave level.

The disadvantages of such an arrangement are apparent when one considers the larger objective of obtaining a reliable digital representation of the true liquid level.

1. For the digital accuracy desired, the level change required to make the kinematic linkage respond is usually too large, and the response is too slow. Gear backlash and the starting friction of the sliding and rolling members cause this reduction in accuracy and response.
2. Such an arrangement requires space in and above the tank whose liquid level is being sensed. The term cumbersome would adequately describe this disadvantage.
3. The delicate digital encoder must be subjected to the environment of the process being measured.
4. Changes in the liquid's specific gravity due to temperature changes can introduce errors in the measurement.

Sensing by Ultrasonic Means

The sensing of liquid level by ultrasonic means is the method of measurement which makes use of the physical properties of sound wave propagation through the liquid. For a liquid at a given temperature, the speed of sound through it is a fixed property. Thus by measuring the transient time of a pulse of sound between its initiation and its reception as a returning echo, the height of a column of liquid can be measured. Since the signal has traversed twice the height of the column, a division by two will yield the correct measurement. The above discussion describes the steps necessary for one to compute the height of a column of liquid when 1. the velocity of sound propagation at 2. a given temperature of the liquid is known. The accuracy of the resulting calculation of the height will depend upon how accurately the velocity of sound propagation is known.

To obtain the level measurement in a digital form by ultrasonic means, a frequency is chosen such that the wave length of the sound through the liquid corresponds to the smallest change of height to be measured.[4] An electronic counter is then counted at this frequency between the initial sound pulse and its returning echo. Then one-half of the number of cycles recorded represents a direct digital measurement of the liquid height. Figure 1 illustrates this measurement technique. Further this figure shows the basic parts of any ultrasonic measuring device. These are the signal source, the projector driver, the sound projector, amplifier,

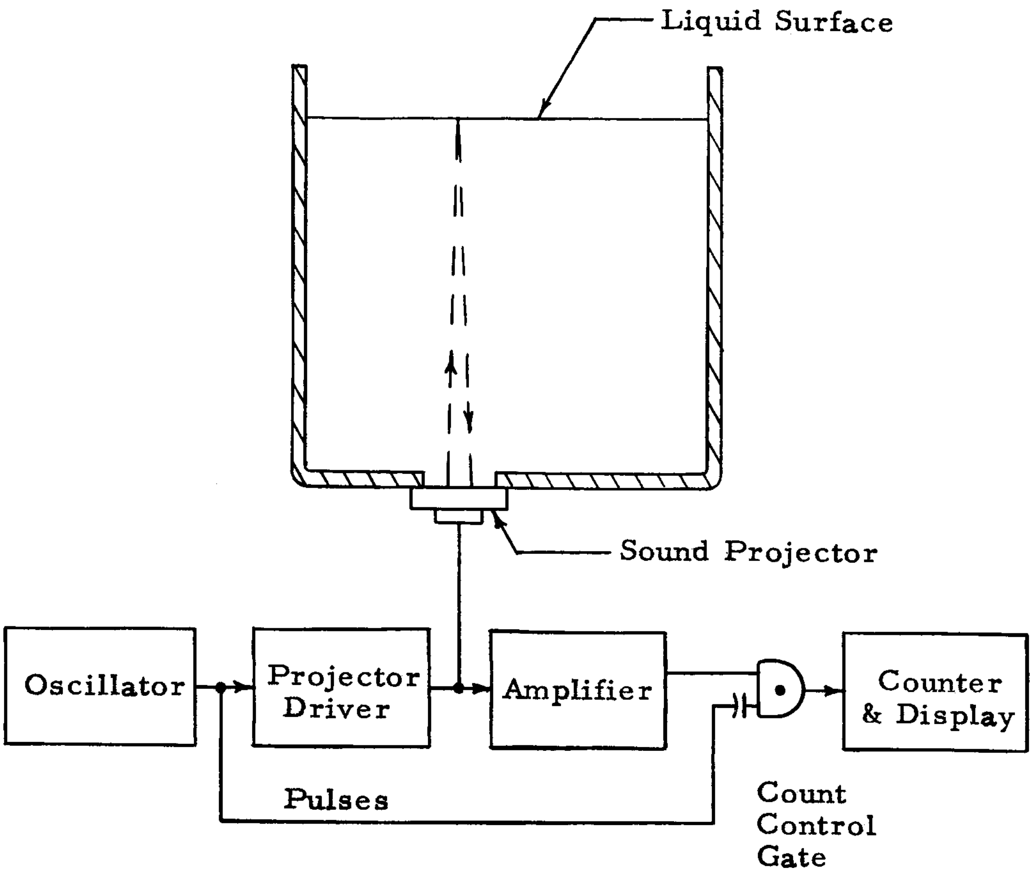


Figure 1. Conventional Ultrasonic Measuring System

and display unit. A receiving transducer would be added to this list if the sound projector were not also used as the receiving unit.

The advantages of the ultrasonic method of measurement are as follows:

1. The digital measurement is made directly. Thus the need for a digital encoder is circumvented.
2. The need for space in and above the liquid which was required by the measurement linkage has been eliminated.
3. By the removal of any moving linkages, the capability for accurate measurement has been increased.

The disadvantages of the ultrasonic method are as follows:

1. The oscillator will require periodic calibration to insure that the frequency of counting will produce the same digital measurement for the same liquid level and temperature.
2. A liquid temperature different from that of calibration will produce a different digital reading for the same liquid level. This objection is analogous to that found in the Bourdon indicator discussion.
3. A basic requirement of the method "...is that the transducer have a very sharp beam angle and that it be free of significant secondary radiation at angles removed from its normal axis."[3]
4. Finally, the implication of using shorter wave lengths of signals in order to insure greater digital accuracy results in a system which responds to surface waves.

Conclusion

Based on the preceding discussion, one can summarize the desirable features of a device which is to measure a liquid level and to provide a digital representation of the measurement. The device should be

1. Accurate and capable of digital read-out,
2. Independent of temperature changes in the liquid,
3. Independent of changes in the liquid's specific gravity,

4. Capable of being subjected to the environment of the process being measured,
5. Independent of measurement techniques which contain large time lags,
6. Independent of measurement techniques which require frequency calibrations,
7. Free from cumbersome kinematic linkages in or above the liquid, and finally
8. Relatively low in cost.

The chapters which follow present the theory, design, and operation of a device which utilizes a number of these desirable characteristics.

CHAPTER II

COMPENSATED LIQUID LEVEL MEASUREMENT

The Digital Liquid Level Transducer is an absolute binary measurement device which obtains the raw liquid level information by ultrasonic means and which processes this information in a limited purpose digital computer to correct it for errors inherent in the ultrasonic measurement method. Thus this compensating level measurement system corrects for the errors in level read-out which are introduced by changes in the velocity of sound which, in turn, result from changes in the temperature of the liquid. Or, in other terms, after installation, the digital transducer requires no manual recalibration because of changes in liquid temperature.

As noted in Chapter I, both the conventional kinematic and ultrasonic methods possess errors in the measurement as a result of variations in the liquid temperature. Hand calculated corrections can be made by a secondary measurement to determine the liquid's present temperature.[2] Yet the complete digital acquisition and correction is not considered. An initial solution scheme which was considered and discarded for this thesis problem was that of obtaining the raw digital measurement by ultrasonic means and correcting the counting frequency of the device by a secondary measurement of the present temperature of the liquid. The introduction of another physical measurement--that of temperature--made this scheme seem impractical. The measurement solution which this thesis describes avoids the need of the temperature measurement. The theory of operation of the digital transducer, which will now be presented, involves both digital and ultrasonic concepts.

Digital Compensation of Measurement

Equation of Operation

The objective of the digital compensation of the liquid level measurement is to provide a true level read-out over a wide range of liquid temperatures without the use of temperature measurement or method of manual calibration. To achieve this, an ultrasonic time measurement over a fixed distance is made simultaneously as the liquid level time measurement is made. Together these two measurements, illustrated in Figure 2, form the input data to the digital calculation device.

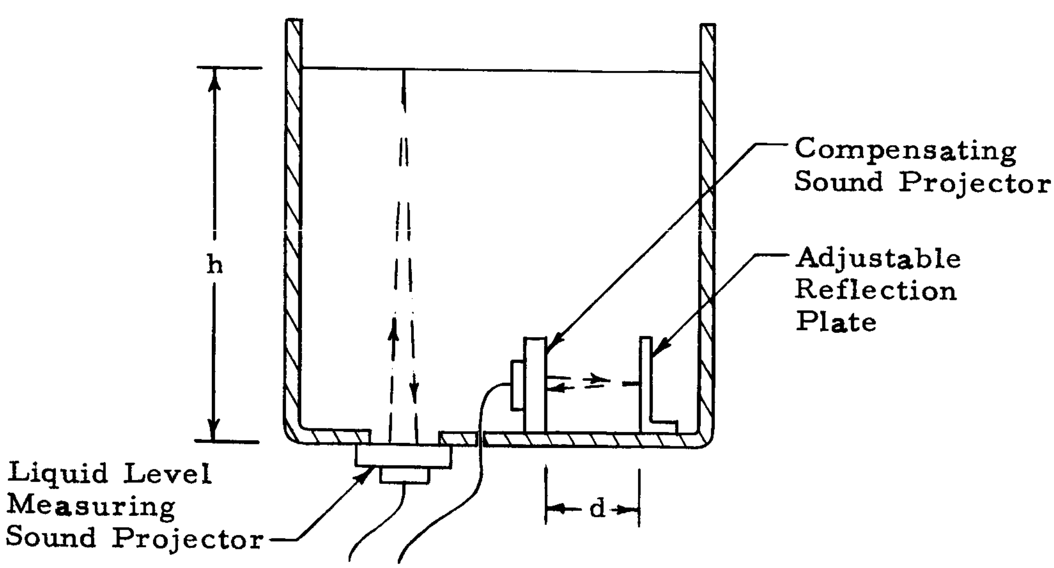


Figure 2. Ultrasonic Measurements

The distance traveled by each ultrasonic pulse is given by

$$2h = v_T \; t_1 \qquad \text{(Measuring Projector)} \qquad (1)$$

$$2d = v_T \; t_2 \qquad \text{(Compensating Projector)} \qquad (2)$$

where v_T = Velocity of longitudinal wave propagation at the liquid temperature T, ft./sec.,

h = Unknown height of the liquid column, ft.,

d = Fixed, known distance between the compensating projector and its reflection plate, ft.,

t_1 = Time interval for the ultrasonic pulse to travel 2h, sec.,

t_2 = Time interval for the compensating ultrasonic pulse to travel 2d, sec.

By eliminating v_T, the combined equations yield the general operating equation of the Digital Liquid Level Transducer, which is

$$h = d\frac{t_1}{t_2} \qquad (3)$$

Physically the introduction of the compensating equation makes each level measurement independent of the liquid temperature.

The computation which the digital device must perform is threefold. Initially the times t_1 and t_2 must be encoded and stored in a digital form for later use. Second, a division computation must be performed which produces the ratio of t_1/t_2. Then the ratio must be multiplied by the distance d. The goal of the following discussions is to explain and to show the relationships among the various measurement parameters of the Digital Liquid Level Transducer.

Time Encoding

The digital encoding of the time interval is accomplished by the use of an oscillator, a counter, and an electronic gate which allows only the oscillation cycles which occur between the initial pulse and its echo to be recorded in the counter. This measurement method is termed "digital" because the interval encoded is expressed as a discrete number of pulses. Since partial cycles are not recorded, the accuracy of the encoding is limited to the time represented by the least significant count which can be registered. This time is the reciprocal of the count frequency, f. An improvement in time encoding accuracy can be obtained by increasing this frequency in order to record more pulses for the encoding of a given interval of time.

To make a discussion of transducer accuracy independent of a particular application, one can discuss measurement accuracy in terms of a ratio. Measurement accuracy is defined as a ratio of the smallest difference between two instrument indications to which a definite numerical value can be assigned divided by the maximum numerical indication which the instrument possesses. Thus the smallest significant unit of information which can be read from a digital instrument is identical to the "smallest difference" mentioned above. Since for digital systems, measurements are defined in terms of quanta or counts, the time encoding measurement accuracy is specified by

$$EA = \frac{\text{Least Count}}{\text{Total Count}} \; 100\% \tag{4}$$

where EA = Encoding measurement accuracy, %,

Least Count = Smallest change in the time encoding measurement to which a definite numerical value can be assigned, fractions of quanta, and

Total Count = q_{max} = Maximum number of whole counts or quanta which define the maximum h which is to be measured, quanta.

Over-all Transducer Accuracy

The same word definition of measurement accuracy can be applied to the over-all accuracy of the transducer system as

$$SA = \frac{(\triangle h)_{min}}{h_{max}} \; 100\% \tag{5}$$

where SA = System measurement accuracy, %,

$(\triangle h)_{min}$ = Smallest change in the height, h, to which a definite numerical value can be assigned, and

h_{max} = Maximum depth which the transducer system can measure.

One will note that no units have been specified for $(\triangle h)_{min}$ and h_{max}. This is explained by noting that the SA is dependent only on the ratio of the sizes of the two quantities and not on their units. Once the SA and h_{max} are specified, the necessary $(\triangle h)_{min}$ is determined. The digital quanta and the physical measurement of the same variable are related by a constant, K. Thus Equation 5 can be expressed as

$$SA = \frac{\Delta h_{min}, \text{ ft.}}{h_{max}, \text{ ft.}} \; 100\%$$

$$= \frac{K\,(\Delta h_{min}, \text{ ft.})}{K\,(h_{max}, \text{ ft.})} \; 100\%$$

$$= \frac{\Delta q_{min}, \text{ quanta}}{q_{max}, \text{ quanta}} \; 100\% \qquad (6)$$

where K = Resultant quantization, quanta/ft.,

Δq_{min} = One quantum, the smallest change in the height, h, which will be digitally recognized in the final answer, and

q_{max} = Total Count = Maximum number of whole counts which define the maximum h which is to be measured, quanta.

A general relationship between the encoding and the system measurement accuracies is given by

$$EA = 1/C\ (SA) \qquad (7)$$

where C = Accuracy coefficient resulting from requirements of factors entering into a numerical calculation.

The accuracy constant C which relates the encoding and the system accuracies is determined by the accuracies of the factors in the operating equation of the transducer.

Computational Accuracies

The accuracy of the quotient of t_1/t_2 is related to the accuracy of the factors t_1 and t_2 by the following:

"The product (or quotient) of numbers is accurate at most to the number of significant figures contained in the least accurate factor. The least accurate factor is the number entering into the computation which has the least number of significant figures."[5]

This statement defines the minimum number of significant figures which each factor must contain for the resultant quotient, t_1/t_2, to have the desired number of significant figures. Also the minimum number of significant figures in each factor for the multiplication of d (t_1/t_2) must be at least equal to the desired number of significant figures in the product, h. In both the multiplication and division operations, it would be more realistic to require that each factor entering into the computation be k times more accurate than the accuracy of the result.

$$(1/k)\,(S_r) = S_f \tag{8}$$

where S_r = Size of the smallest unit of measure in the resultant,

S_f = Size of the smallest unit of measure in the least accurate factor, and

k = Encoding accuracy factor, ratio of the size of the smallest unit of measure in the resultant to that in the least accurate factor.

This statement will be used as a guide for each of the factors entering into the calculation.

The required accuracies of each of the factors in the operating equation of the Digital Liquid Level Transducer can now be expressed in terms of the required size of the smallest unit of measure in the resultant, h. For the multiplication h = (d) (t_1/t_2), the factors d and t_1/t_2 must have their smallest units of measurement k times smaller than those of h. Further, for the division operation t_1/t_2, each of these time factors must have its smallest unit of measure k times smaller than that in the resultant t_1/t_2. Thus each time must have its smallest unit of measure k^2 times smaller than the smallest unit in h. The accuracy coefficient C in Equation 7 is $C = k^2$, and the encoding measurement accuracy is given by

$$EA = \frac{SA}{k^2} \qquad (9)$$

This statement relates the encoding measurement accuracy to the system measurement accuracy by the square of the ratio of the size of the smallest unit of measure in a resultant calculation to the corresponding unit of the least accurate factor entering into the calculation. The k^2 term appears, since two calculations have been used to transform the time encoding data into the final compensated height, h.

Multiplication Without Calculation

In the preceding discussions, nothing has been mentioned about the initial selection of the fixed, measured distance d. In truth, the distance d can be anything one desires; yet by a judicious selection of this distance, one can simplify the calculation operations. The decimal number system will provide an example.

Multiplication by a multiplier such as 100 is quickly accomplished by shifting the decimal point in the multiplicand to the right the number of places equal to the number of zeros in the multiplier. Division by such a number is equally easy, since the decimal point is shifted to the left according to the number of zeros in the divisor. Therefore, without formal calculation, one can multiply by such a number by shifting the decimal point.

The application of this technique to the digital transducer is illustrated by the following. Suppose that the time measurements of t_1 and t_2 are recorded as

$$t_1 = 856.6 \ \mu\,\text{seconds, and}$$
$$t_2 = 115.3 \ \mu\,\text{seconds.}$$

By following the instructions specified by Equation 3, the ratio of t_1/t_2 is determined in the computer as 7.42. Now if d is defined to be 100 quanta, the final result, h, is 742 quanta; and the second calculation, namely (d) (t_1/t_2), has been avoided.

Based on this desirable specification of d, the number of explicit calculations has been reduced to one. The accuracy coefficient, C, is equal to k, and Equation 7 becomes

$$EA = \frac{SA}{k} \tag{10}$$

if and only if d is specified as $(1000\ldots0.)_r$ in some desirable number system whose base is r.

In terms of the quantities in Equations 4 and 6, Equation 10 becomes

$$\text{Least Count} = (1/k) \, \Delta q_{min} \tag{11}$$

Synchronization of the Oscillator Frequency

Equation 3 contains a subtle implementation situation which will now be explored. The resultant number of quanta, which is encoded during a time measurement, will depend on the synchronism or lack of it between the counting pulses from the oscillator and the start signal. This, in turn, could affect the accuracy specified by Equation 6. Figure 3 presents the synchronous and nonsynchronous cases.

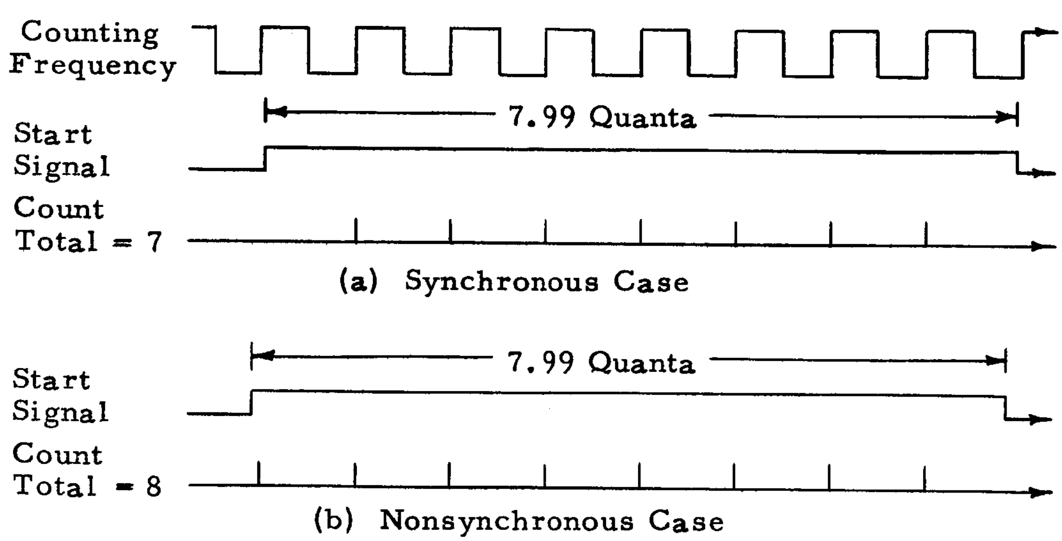


Figure 3. Synchronization of Oscillator Frequency and Start Signal

For illustration purposes, the exact depth in number of quanta which is to be encoded is 7.99. Since, in the synchronous case, the oscillator frequency is required to be in synchronism with the start signal, repeated measurements of the same depth will yield the same answer. For each measurement, one complete cycle occurs before one unit is counted into the counter. Yet each measurement is in absolute error by 0.99 quanta.

If the oscillator frequency is not required to be in synchronism with the start signal, then the best case occurs when the counter counts a pulse just after the start signal has occurred. For this measurement, the counter registers 8 counts which is 0.01 quanta greater than the exact measurement. Yet if the nonsynchronous case is used in a second measurement, the counter may register 7 or 8 depending on the relationship of the start signal and first count pulse from the oscillator. By this presentation, one can conclude:

1. that in both cases the maximum error in measurement will be less than, or at most, equal to one quanta,
2. that the advantage of the synchronous scheme is that repeatability of the measurement is insured, and
3. that the absolute error can be reduced in both cases by increasing the counting frequency and reducing the size of the quanta by a proportional amount.

The preceding conclusions illustrate that for a given time quantization as specified by the counting frequency, the synchronous case has no advantage over the nonsynchronous, since the maximum margins of uncertainty in the answers are identical.

Transducer Equation Implementation

Implementation of the operating equation of the Digital Liquid Level Transducer, Equation 3, will now be presented for the purpose of describing further accuracy considerations which are involved in the technique. The implementation can best be described in terms of the measurement and calculation operations.

The measurement operation is performed by counting two counters in the forward direction at the same measurement frequency, f_m, for time durations which are equal to t_1 and t_2. The count totals, A and B, which are recorded in the counters, will be proportional to the times t_1 and t_2, respectively. Equations 12 and 13 result.

$$f_m t_1 = A \tag{12}$$

$$f_m t_2 = B \tag{13}$$

The measurement operation is illustrated in Figure 4.

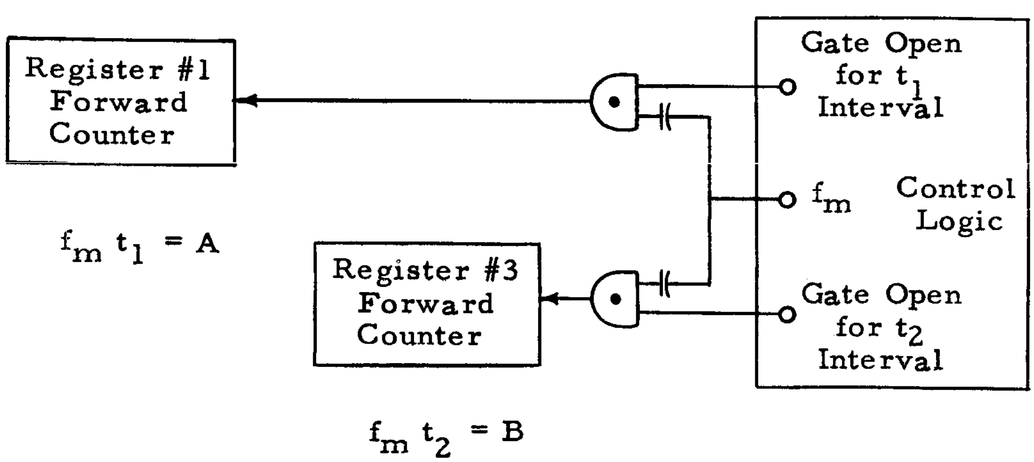


Figure 4. Measurement Operation

The calculation operation of the digital transducer is performed by a frequency multiplying technique.[6] By this technique, the output of an operational multiplier, whose input frequency is f_c, is a second frequency, (f_c B), where B is a fixed numeric input which is less than one. Figure 5 presents this concept.

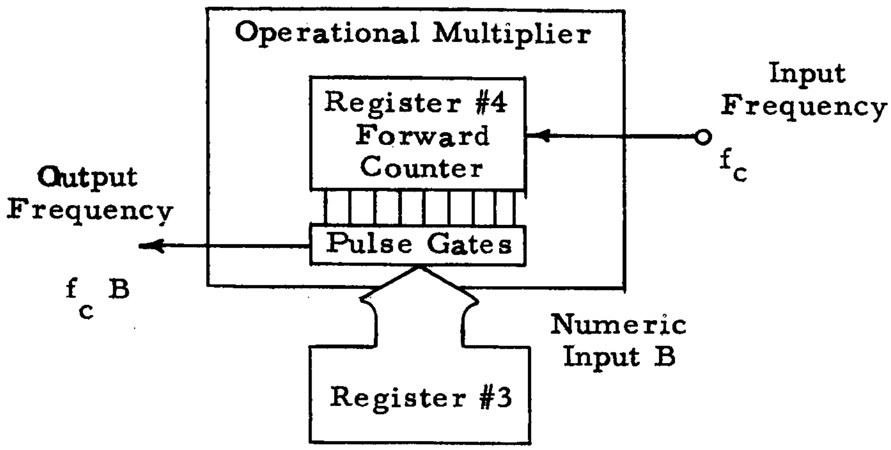


Figure 5. Operational Multiplier

The function of the operational multiplier in the digital transducer calculation operation is to perform the calculation t_1/t_2 by using the pulse train, f_c, modified by the numeric B.

Count total A, which was obtained in the measurement operation, is set into a second counter, Register #2. This counter counts backward, since for each input pulse, the count total is reduced by one. The input pulses to this backward counter are generated by the output (f_c B) of the operational multiplier as illustrated in Figure 6.

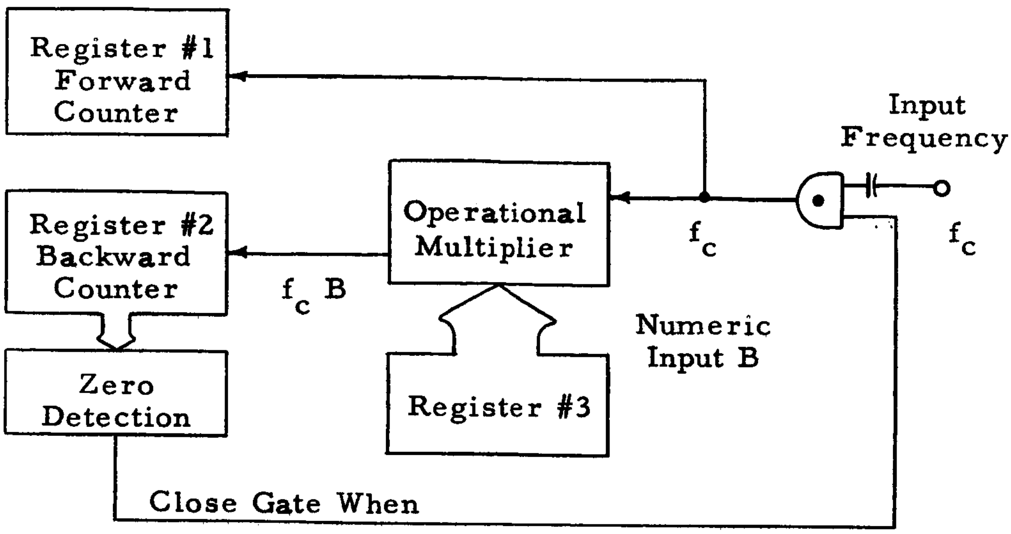


Figure 6. Calculation Operation

The reduction of the Register #2 contents to zero will require a calculation time, t_c. Thus the statement relating the original contents, A, to the input frequency, (f_c B) is

$$A = f_c B t_c \tag{14}$$

During this same calculation time, t_c, Register #1 is counted forward from zero at the fixed rate of f_c. Equation 15 describes this resultant total count, R.

$$R = f_c t_c \tag{15}$$

By eliminating t_c, Equations 14 and 15 combine to yield

$$R = f_c \frac{A}{f_c B} \tag{16}$$

Finally, A and B, which are defined by Equations 12 and 13, can be substituted into the above equation to produce

$$R = f_c \frac{f_m t_1}{f_c f_m t_2} \tag{17}$$

Since the fixed distance, d, is a multiplier of the form (100... 0.), the compensated liquid height measurement, h, is expressed by

$$h = (d) R$$

or

$$h = d \frac{f_c f_m t_1}{f_c f_m t_2} \tag{18}$$

where
- h = Compensated liquid level measurement, quanta,
- d = Fixed distance measurement of the form $(100\ldots0)_r$, quanta,
- f_c = Frequency of the pulses used in the calculation operation, pulses/sec.,
- f_m = Frequency of the pulses used in the measurement operation, pulses/sec.,
- t_1 = Time interval for the ultrasonic pulse to travel 2h, sec., and
- t_2 = Time interval for the compensating ultrasonic pulse to travel 2d, sec.

Equation 18, which expresses the calculation result of the digital device, demonstrates the independency of the resultant upon the frequencies of calculation and measurement. It will be recalled that other level indicating digital devices required the maintenance of a frequency as a calibrated measurement standard.

By the comparison of Figures 4 and 6, it will be seen that

Register #1 is utilized twice during the operation cycle. First, it is used to record the encoding of time, t_1; then during calculation, it is used to record the final result, h. By time sharing Register #1, the need for a second forward counting register has been averted.

Register Capacities

The total count requirements for Registers #1 and #3 for the time encoding of t_1 and t_2, respectively, are determined by the product of three factors: the maximum ultrasonic path length, $2h_{max}$, the resultant quantization, K, and encoding accuracy factor, k. The count capacities of Registers #1 and #3 become

$$\text{Total Count Register \#1} = 2h_{max}\,K\,k \tag{19}$$

$$\text{Total Count Register \#3} = 2d\,K\,k \tag{20}$$

Because Register #2 (backward counter) is to receive the encoded time, t_1, its size is also determined by Equation 19.

Ultrasonic Considerations

The ultrasonic concepts which are involved with the analytical development of the Digital Liquid Level Transducer are based on the transmission equation of the longitudinal wave and on the characteristics of the liquid and its echo reflection interface. Also related to the digital transducer is the concept of signal attenuation.

Longitudinal Wave Transmission

The forward velocity of propagation of a sound wave is caused by sinusoidally alternating compressions and rarefactions in the medium. The velocity of propagation of such a wave is given by

$$v_T = f_m \lambda \tag{21}$$

where v_T = Velocity of longitudinal wave propagation at the liquid temperature, T, ft./sec.,

f_m = Frequency of the pulses used in the measurement operation, cycles/sec., and

λ = Distance, wave length, between two successive points in the disturbance having the same phase, ft./cycle.[4]

For distance encoding purposes, the maximum measurement accuracy for a given liquid and a given frequency of disturbance is the wave length, λ. Thus the longitudinal wave equation is related to the distance corresponding to the least count of Equation 11. Since the quantization in the final result is K quanta/ft., and since the Δq_{min} is defined to be one quantum, Equation 11 becomes

$$\text{Least count distance, ft.} = \frac{1 \text{ quantum}}{k\,K \text{ quanta/ft.}} \tag{22}$$

The limiting case defining the required λ is found by equating the least count distance, Equation 22, to λ.

$$\lambda = \text{Least count distance} = \frac{1}{k\ K} \tag{23}$$

Then Equation 21, when rearranged becomes

$$f_m = \frac{v_T \, k \, K}{1 \text{ quantum}} \tag{24}$$

where f_m = Frequency of the pulses used in the measurement operation, cycles/sec.,

v_T = Velocity of longitudinal wave propagation at the liquid temperature T, ft./sec.,

k = Encoding accuracy factor, ratio of the size of the smallest unit of measurement in a resultant to that of the least accurate factor used in the calculation of the resultant, dimensionless, and

K = Resultant quantization, quanta/ft.

Wave Length, Quantization, and Surface Waves

High resultant quantizations, K, are related to the measurement wave length and to the surface waves of the liquid. By specifying high quantizations, the wave length of the ultrasonic frequency must become proportionally short. This can be seen in Equation 23. Yet this is not the only result.

The higher quantizations enable the measurement device to distinguish between the crests and hollows of a surface wave whose vertical distance is greater than λ. Since the purpose of the high quantization is to distinguish a liquid height change which is equal to λ, the presence of surface waves must be eliminated. Thus in the region of the surface from which the ultrasonic echo will be reflected, some physical provision must be made to insure that the surface waves which are present are small in comparison to λ. This may require nothing more than a baffle to prevent liquid splash from affecting the liquid surface which is to be measured.

Velocity Characteristics

The velocity of propagation of a longitudinal wave in the liquid is important to the analytical development of the digital transducer. Equation 24 demonstrates this. Of equal importance to the calibration of the instrument is the variation of the velocity with liquid temperature. The velocity of sound in liquids usually has a negative temperature coefficient. This means that the velocity decreases with increasing temperature. Water with its positive coefficient is a notable exception. Of importance to the calibration of the digital transducer is not the magnitude of the velocity change, but rather the sign of the temperature coefficient. To illustrate this, the following is presented.

For any digital transducer application, one will know the liquid and the liquid temperature range over which operation is desired. Further, the approximate velocities of wave propagation at these extreme temperatures and the sign of the temperature coefficient of velocity will also be known. With this information, one can determine the worst case requirement for the wave length λ.

For a constant frequency of disturbance, the temperature extreme which has the larger velocity of sound propagation determines the largest λ which is acceptable for the required measurement accuracy. At all lower velocities the quantization will be better than desired, since the wave length will be shorter. Thus Equation 24 must be rewritten as

$$f_m = \frac{v_l \, k \, K}{1 \text{ quantum}} \tag{25}$$

where v_l = Larger velocity of wave propagation of the two temperature extremes, and

v_s = Smaller velocity of wave propagation of the two temperature extremes.

One can now state that

1. If the temperature coefficient of velocity is positive, then v_l occurs at the high temperature extreme, and
2. If the temperature coefficient of velocity is negative, then v_l occurs at the low temperature extreme.

The sign of the temperature coefficient of velocity also determines the final adjustment of the compensating distance, d. As illustrated in Figure 2, the distance, d, can be adjusted by moving the reflection plate forward or backward over a small range. This adjustment is necessary because the distance, d, cannot be measured physically, since the distance that the sound projector crystal face lies within the protective covering is not known.

It is necessary to set the distance, d, by utilizing the Register #3 readings of the transducer itself. Equation 2 states that for a given distance, d, the smallest velocity of sound propagation, v_s, will produce the largest time, t_2, which must be encoded. This largest count must equal the total count capacity of Register #3. Calibration is achieved by placing the compensating sound projector and reflection plate in the liquid at the temperature extreme which produces the smaller velocity of sound propagation. Then the distance, d, is adjusted until the encoded t_2 measurement produces the maximum count in Register #3. One can now state that

1. If the temperature coefficient of the velocity is positive, then v_s occurs at the low temperature extreme; and the distance, d, must be adjusted at that temperature, and
2. If the temperature coefficient of the velocity is negative, then v_s occurs at the high temperature extreme, and the distance, d, must be adjusted at that temperature.

Echo Reflection Interface

The physical arrangement of the measuring sound projector as shown in Figure 2 implies that the ultrasonic energy, which enters the liquid from the sound projector, travels to the liquid interface where it is reflected back to the original source as an echo. The requirements of a good interface, i.e., one which reflects most of the incident energy, will now be presented.

Figure 7 illustrates the interface between two different media. The characteristic impedence of each are given by

$$Z_1 = \rho_1 v_1 \tag{26}$$

$$Z_2 = \rho_2 v_2 \tag{27}$$

where Z_i = Characteristic acoustic impedence of each medium [mechanical impedence (force/velocity) per unit area], (lb. sec.)/ft.^{3},

ρ_i = Density of each medium, slugs/ft.^{3}, and

v_i = Velocity of longitudinal wave propagation of each medium, ft./sec.

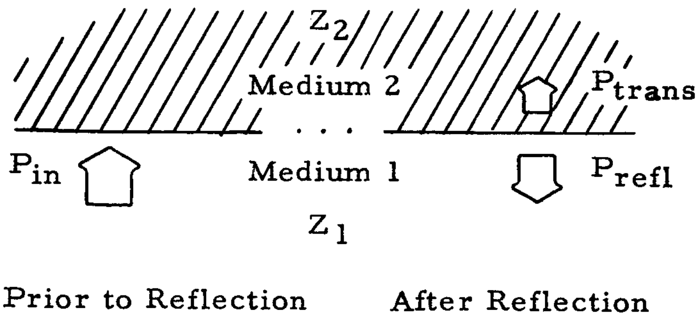


Figure 7. Reflection at the Interface

The pressure waves at each side of the boundary must satisfy two conditions: (1) the total pressure must be the same, and (2) the particle velocity into the boundary must equal the particle velocity out of the boundary on the other side.[7] From these considerations the general formulas result.

$$\frac{P_{refl}}{P_{in}} = \frac{Z_2/Z_1 - 1}{Z_2/Z_1 + 1} \tag{28}$$

and

$$\frac{P_{trans}}{P_{in}} = \frac{2(Z_2/Z_1)}{Z_2/Z_1 + 1} \tag{29}$$

where P_i = Maximum instantaneous pressure amplitude of the incident, reflected, and transmitted waves.

For the Digital Liquid Level Transducer, one would like the ratio P_{refl}/P_{in} to be as close to 1 as is possible. Thus if $Z_2 \ll Z_1$, $P_{refl} \approx -1\ (P_{in})$, where the -1 indicates a phase reversal, and

P_{trans} is almost zero. For $Z_2 \gg Z_1$, $P_{refl} \approx P_{in}$, but $P_{trans} \approx 2P_{in}$. Thus if the designer of the ultrasonic equipment had a choice (in a given application, he usually doesn't), he would like to use an interface which is characterized by $Z_2 \ll Z_1$.

Propagation Loss

Future measurement applications which embody the concepts of the Digital Liquid Level Transducer will be determined to a great degree by the purely ultrasonic phenomenon of propagation loss. It is this loss in a given liquid at a given ultrasonic wave frequency that will determine the depths which can be successfully measured for the electrical energy which must be expended in the sound projector.

Propagation loss is the sum of two types of acoustic energy attenuations. They are spreading and attenuation losses.[8] Spreading loss results from the divergence of energy over an ever increasing area. It is independent of frequency. Under ideal conditions, the spreading loss obeys the inverse square law. The intensity of the acoustic energy is inversely proportional to the square of the distance which it has traveled from a point. The attenuation loss results from the absorption of the energy by the medium. This loss, while being independent of the length of the path, is a function of the frequency of the acoustic wave generated. Thus to discuss the feasibility of a given application, one must specify the liquid, the frequency, and the distance to be measured.

In this general discussion, however, it is more desirable to discuss propagation requirements by specifying only the liquid. This is possible by selecting one frequency and by observing the absorption per unit length of path for various liquids. Various ultrasonic investigators have done just this.[9] Their results indicate that the absorption coefficients are greater than those calculated on the assumption of purely viscous losses. Based on the observations of Teeter, Table 1 presents selected liquids whose absorptions were determined at room temperature for an ultrasonic wave frequency of 15 Mc. /sec.

Inorganic Salt Solutions	Absorption coefficient for power, db/meter
Sodium chloride (saturated)	85
Sodium bromide (saturated)	65
Synthetic sea water	120
Ammonium chloride (saturated)	90
Hydrogen chloride (pH1)	70
Organic Liquids	
Benzene	1350
Ether	210
Acetone	75
Ethyl alcohol	500
Water (24°C)	75

Table 1. Energy Absorptions for Various Liquids At a Wave Frequency of 15 Mc. /sec.

It is interesting to note that Teeter reports the power absorption coefficient of water at 24°C resulting from an ultrasonic frequency of 10 Mc./sec. to be 50 db/meter. Thus the attenuation loss as a function of frequency is demonstrated.

CHAPTER III

LOGICAL IMPLEMENTATION OF THE DIGITAL LIQUID LEVEL TRANSDUCER

Statement of the Measurement Problem

For the purpose of demonstrating the validity of the concepts of the Digital Liquid Level Transducer, a measurement problem in the Numerical Control Laboratory of Case Institute of Technology was chosen. This problem involved the digital encoding of water level information by using a float and linkage system connected to a ten binary bit absolute brush encoder which provided feedback information to several generations of digital controllers. The measurement problem specification is as follows:

Liquid:	Water
Measurement range:	2 feet
Accuracy:	± 0.1% of the full range
Temperature extremes of liquid:	40 to 100°F
Digital output:	Absolute binary
Number of complete operations per second:	4 (minimum)

Based on this statement, a Digital Liquid Level Transducer has been logically implemented to perform the same measurement operation.

Transducer Requirements

The operational requirements of the Digital Liquid Level Transducer are:

1. To meet measurement problem specifications.
2. To provide for parallel binary read-out,
3. To provide for serial binary read-out, both most significant and least significant bit first, and
4. To utilize, if desirable, commercially available sound projectors and sound projector drivers.

Information Representation

The selection of the binary number system for the measurement and calculation operations in the digital transducer is a natural outgrowth of the problem specification that the resultant measurement will be in binary. By using a single number system throughout, no number system conversions were required; and complexity of the system, which could result from code conversions, was circumvented.

Problem Calculations

The logical implementation of the transducer rests on the accuracy, frequency, and total count equations which were developed in Chapter II. The accuracy of the over-all measurement is specified to be $\pm 0.1\%$ of full range. This then defines the smallest unit of height to which a definite numerical value can be assigned over a 2 foot range. Thus by employing Equation 5

$$\Delta h_{min} = \frac{(0.1\%)\ (2\ ft.)}{100\%} = 0.002\ ft.$$

Since Δq_{min} is defined to be one quantum, Equation 6 states that

$$q_{max} = \frac{1\ quantum}{0.1\%}\ (100\%) = 1000\ quanta$$

Also from Equation 6, the resultant quantization is

$$K = \frac{\Delta q_{min}}{\Delta h_{min}} = 500\ quanta/ft.$$

Before the operational requirements can be completely specified, two design choices must be made--the selection of the compensating distance, d, and the determination of k. The factors which contribute to the decision on d are as follows:

1. The use of a short distance is desired in order to keep the assembly of the two sound projectors relatively small.
2. The distance, d, must be specified as a binary number, i.e., 100...00 as required by Equation 10.

By selecting a compensating distance of d = 0.256 ft., both factors were considered. For the quantization of 500 quanta/ft., the compensating distance in quanta becomes

$$d = (500\ quanta/ft.)\ (0.256\ ft.) = 128\ quanta$$

The binary representation for 128 quanta is $(10000000)_2$ which meets the requirement of Equation 10.

The factors which contribute to the selection of k, the ratio of the smallest unit of measurement in a resultant calculation to the smallest unit in the least accurate factor, are as follows:

1. To obtain an accurate calculation resultant, k should be as large as is practical.
2. The ratio should be easily represented in the binary. Thus k should be of the form $2^0, 2^1, 2^2, \ldots, 2^n$.
3. The effects of trial values of k can be observed in the measurement frequency and propagation losses of Equation 25 and Table 1, respectively.

By applying Equation 25 and by using v_l = 5000 ft./sec. for water and K = 500 quanta/ft., the effect of k on f_m is observed.

If k equals	Then f_m equals
$2^0 = 1$	2.5 Mc./sec.
$2^1 = 2$	5.0 Mc./sec.
$2^2 = 4$	10.0 Mc./sec.
$2^3 = 8$	20.0 Mc./sec.

The ultrasonic absorption coefficients for water are 75 db/meter at 15 Mc./sec. and 50 db/meter at 10 Mc./sec., as presented in Table 1. Thus from the ultrasonic projector drive requirements, ratios of 8 and 4 are not desirable. A value of k = 1 is equally undesirable, since the smallest unit of a calculation factor would be equal to the smallest unit of the resultant. Thus both ultrasonic and analytic considerations bracket the ratio of k = 2 which is used in the digital transducer.

The register capacities for the encoding of times, t_1 and t_2 can now be specified. The total count requirements for Register #1 and #3 are described by Equations 19 and 20, respectively.

$$\text{Total Count Register \#1} = 2(2 \text{ ft.})(500 \text{ quanta/ft.})(2)$$
$$= 4000 \text{ counts}$$
$$\text{Total Count Register \#3} = 2(0.256 \text{ ft.})(500 \text{ quanta/ft.})(2)$$
$$= 512 \text{ counts}$$

The register capacities have been stated in "number of counts" in order to have the term "quanta" apply only to the resultant quantization. Another observation is that q_{max} = 1000 quanta; yet this value is only one-quarter the size of Register #1. This results (1) from the time being encoded over a distance of $2h_{max}$ and (2) from the use of k = 2 in order to insure numerical accuracy in the digital computation.

Register #1, in binary representation, must be capable of at least the 4000 count capacity. Since 2^{12} equals a total count of 4096, then Register #1 (and backward counting Register #2 also) must consist of 12 binary bits. Because of the judicious choice of d, Register #3 will consist of 9 binary bits.

Timing Specifications

The intervals of time required for the measurement and the complete operation are determined by the smallest velocity of sound propagation and by the number of complete operations which must be made in a second. The difference between these two times determines the maximum available calculation time.

The velocity of sound in water for the two temperature extremes, after unit conversions, is given by the following:[10]

$v = 4710$ ft./sec. at $40^{\circ}F$

$v = 4950$ ft./sec. at $100^{\circ}F$

Also this author provides a vast list of compounds, their velocities, and temperature coefficients of velocity.

The maximum measurement time, t_m, results from measuring the maximum level at the smaller velocity of the two temperature extremes. Thus by applying Equation 1,

$$t_m = 2(2 \text{ ft.})/(4710 \text{ ft./sec.}) = 849 \ \mu\text{sec.}$$

where t_m = The maximum measurement time required by the digital transducer.

The maximum complete operation time is specified by the reciprocal of the required 4 operations per second. Thus the maximum calculation time, t_c, plus the maximum measurement time, t_m, must be less than or equal to one-quarter of a second. Finally, one can state that the calculation time is

$$t_c \leq (250{,}000 - 849) \ \mu\text{sec.}$$

where t_c = The maximum available calculation time which the digital transducer may utilize.

Measurement Frequency

The relationship between the velocity of sound in the liquid and its temperature specifies the measurement frequency for the digital transducer. After noting that the measurement frequency requires the larger of the two velocities, Equation 25 becomes

$$f_m = \frac{(4950 \text{ ft./sec.})(2)(500 \text{ quanta/ft.})}{1 \text{ quantum}}$$

or $$f_m = 4.95 \text{ Mc./sec.}$$

Calculation Frequency

The calculation frequency of the digital transducer is primarily determined by the maximum available calculation time as discussed in the Timing Specifications. A more complete statement of the calculation frequency is given by rearranging Equation 15.

$$f_c = \frac{R}{t_c}$$

In the worst case, R can become the full count capacity of 4000. Thus

$$f_c = \frac{4000}{0.249 \text{ sec.}} = 16 \text{ kc./sec.}$$

As a result, if f_c is chosen equal to or greater than 16 kc./sec., the complete operation requirement of 4 per second will be met.

Water and Air Interface

With the application for the Digital Liquid Level Transducer now defined, one can discuss the echo reflection capability of the water and air interface. By applying Equations 26 and 27, the characteristic acoustic impedence of each medium is determined.

$$Z_{water} = (1.93 \text{ slugs/ft.}^3)(5000 \text{ ft./sec.})$$
$$= 9650 \text{ (lb. sec.)/ft.}^3$$
$$Z_{air} = (0.0023 \text{ slugs/ft.}^3)(1126 \text{ ft./sec.})$$
$$= 2.59 \text{ (lb. sec.)/ft.}^3$$

The ratio of the water impedence to that of the air is approximately 3700. By Equation 28, the maximum instantaneous pressure amplitude of the reflected wave is practically identical to that of the incident wave. The transmitted pressure amplitude is virtually zero by Equation 29. From this discussion one can conclude that since the change in acoustic impedence in passing from water to air is so great, the interface becomes almost a perfect reflector for underwater sound.

Considerations of Design

The need to physically implement the concepts of the Digital Liquid Level Transducer gives rise to problems of design for which there is no single solution. The purpose of this chapter division is to discuss three areas in the digital transducer which contain such design considerations.

Timing Design

That part of the digital transducer which provides control and direction for the equipment which performs the measurement and calculation operations is called the timing or control logic. Basically this logic must receive and record a start operation signal, cause registers to be cleared, cause the ultrasonic pulses and the time encoding to begin, cause the calculation to occur, and prepare itself for the reception of the next start signal. The cyclic nature of its operation suggests two possible implementation techniques. These are the monostable multivibrator and the gated techniques.

The monostable multivibrator or one-shot technique involves the use of devices of the same name to satisfy the control required. The one-shot, as its informal name implies, has one stable state. On receipt of an operate pulse, the device is upset from its stable state into a second quasistable state. There it remains for a fixed time delay, after which the one-shot returns to its former stable state. Thus the timing of the digital transducer might consist of a chain of one-shots whose time delays in the upset state are equal to the time requirements of the various operations in the transducer. As one device returns to its former state, it would cause the upsetting of the next device.

The advantages of such a technique are its straight forward logical concept and its lower expense. Its disadvantages are primarily physical.

1. Each device must be individually adjusted to provide the

correct delay.

2. The timing cannot be made to sequence slowly to enable trouble shooting by observing panel lights as indicators.
3. Should the measurement range be altered, each of the one-shots would need to be readjusted.

The gated technique for the timing utilizes a master clock whose output pulses are counted in a timing counter. Logical (voltage level operated) gates are then used to sense the count total in the timing counter. By this arrangement the gated technique produces the time requirements of the various operations in the transducer. Figure 8 illustrates the gated timing concept.

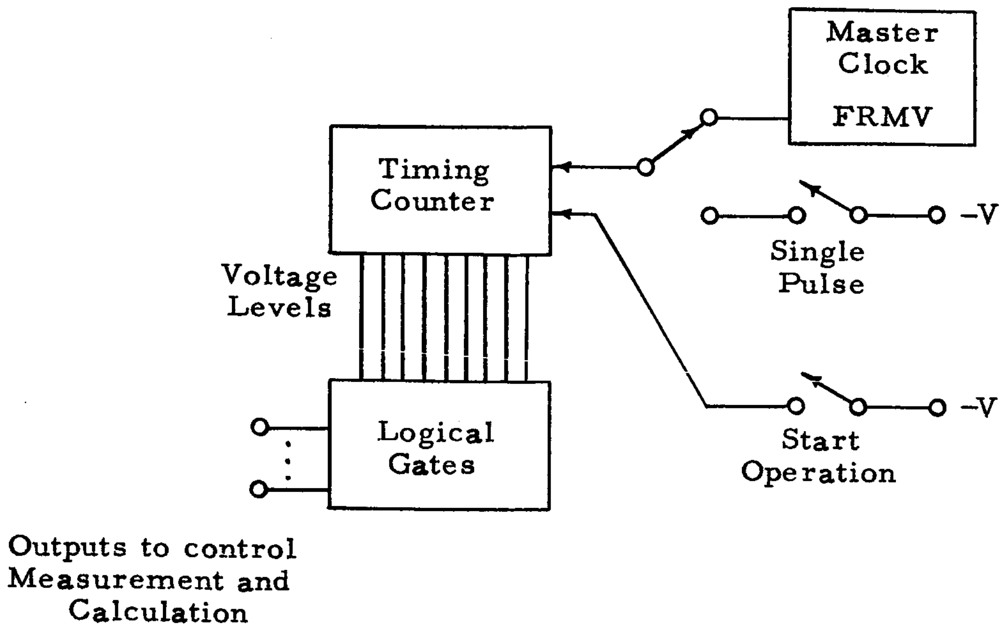


Figure 8. Gated Timing Technique

The advantages of the gated timing technique are summarized as follows:

1. The timing is dependent solely on the master clock adjustment. This clock is normally called a free running multivibrator, FRMV.
2. By the use of a manually operated switch, the entire timing can be made to sequence slowly for visual sub-system check out.
3. Altering the measurement range requires a simply instrumented pulse division of the free running multivibrator frequency.

The disadvantage of the gated timing technique is that the scheme requires approximately 1/3 more logic (8 transistors) than does the simpler one-shot technique.

The design decision to utilize the gated technique in the logical implementation of the digital transducer timing is based on an experimental need of developing a transducer timing system which can be easily checked and changed if the need arises. In short, the advantage of the gated technique is its experimental flexibility.

Oscillator and Ultrasonic Pulse Independency

The design decision to allow the oscillator frequency to function independently of the ultrasonic start signal is based on the Chapter II discussion of the Synchronization of the Oscillator Frequency. This discussion concluded that for a given counting frequency, the maximum count error was independent of the relationship between the oscillator frequency and the start signal. Thus to logically require such synchronism of frequency and signal would add nothing to the digital transducer except complexity.

Start Operation Pulse Coincidence

An outgrowth of the decision to use the gated timing scheme is the pulse coincidence problem at the start of the operation cycle. Basically the timing counter can receive pulses from the free running multivibrator and from the start operation switch. If these two pulse sources provide pulses which are close together in time, one can rightfully ask what the timing counter will recognize.

1. If the timing counter recognizes the pulses as one, then the counter will count to one and will remain at this count level for one complete cycle of the FRMV. The next pulse from the FRMV will carry the count to two, and correct operation will continue.
2. If the pulses are close together in time but are not coincident, then the timing counter will record both of them; and the time that the counter is at the count one level will be greatly shortened. Further, one cannot specify the time duration of the one count.

To avoid the use of anti-coincidence logic in order to assure the constant separation of the pulses, the flexibility of the gated technique was used to obtain a simpler solution. This involved defining count one to be a "No operation" count. Thus the time duration of count one was made immaterial to the operation of the digital transducer.

Transducer Operation

The digital transducer operation will be presented by describing the sequence of events in one cycle of operation. The individual operations of the circuit modules which constitute the transducer sub-systems are discussed in Appendix A. The circuit schematics and logical symbols are also presented. Appendix B presents the consideration of forward and backward binary counting.

Measurement Operation

The measurement operation in the digital transducer is divided into three steps. These are initialization, ultrasonic projection, and echo reception. Figure 9 illustrates these three steps. The function of the initialization is to ready the control logic and the registers for the approaching measurement and calculation operations. Initialization includes the following:

1. Flip-flops of Registers #1 and #3 are reset. This action insures that the measurement operation starts with no count totals in the registers which will encode the times t_1 and t_2.
2. Control flip-flops E_1 and E_2 are set. These memory units record the reception of ultrasonic echos. Thus they control the counting in Registers #1 and #3.
3. Prior to initialization control flip-flop E_0 was reset.

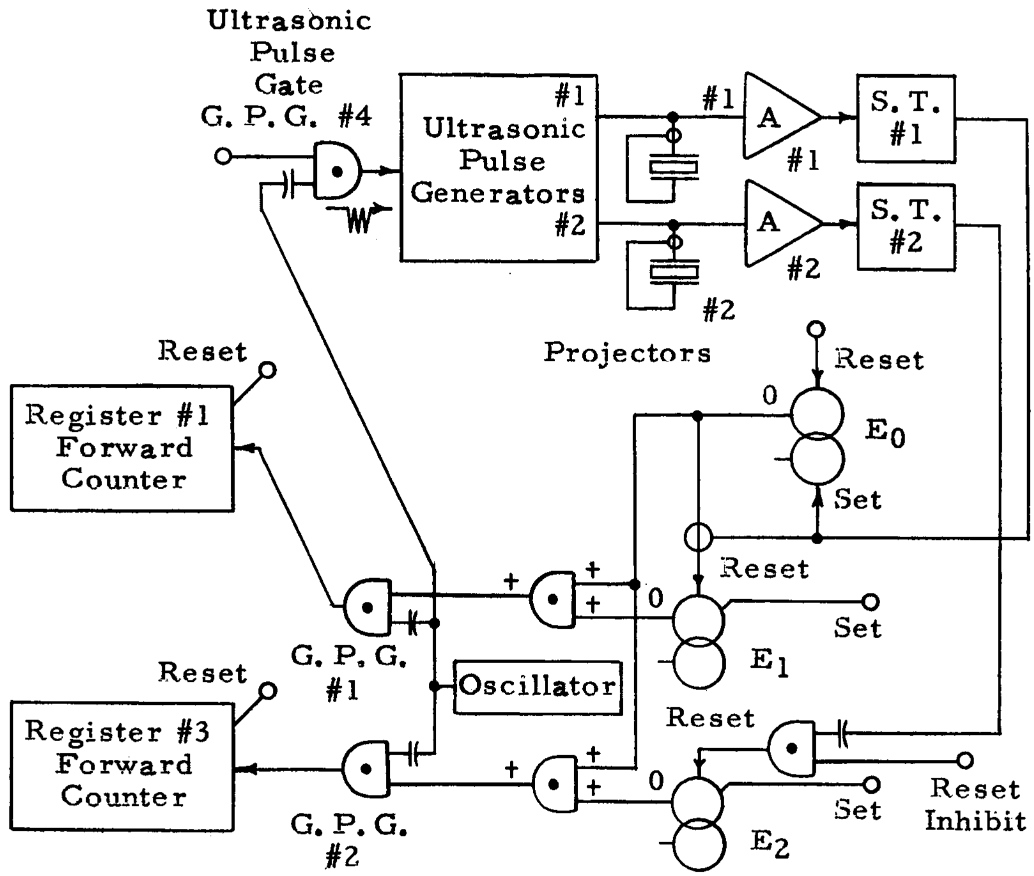


Figure 9. Measurement Implementation

Ultrasonic projection includes those operations which produce and send the ultrasonic signals into the water. The projection requires the following:

1. The ultrasonic pulse gate, G. P. G. #4, is opened for a specified time. During this time the oscillator signal drives each sound projector through the corresponding ultrasonic pulse generator.
2. These driving signals are coupled through the amplifiers and the Schmitt trigger squaring circuits to the control

flip-flops E_0 and E_2.

3. Flip-flop E_0 is set. This action simultaneously allows gated pulse generators #1 and #2 to transmit count pulses to Registers #1 and #3, respectively.
4. No change of state has occurred in flip-flop E_2, since the resetting action was logically inhibited by the reset inhibit signal.

The echo reception involves the control actions which are taken to stop the counting in Registers #1 and #3 when the echos are received. For the t_1 encoding, the following occurs:

1. When the echo from the surface of the liquid is received, it is amplified, squared, and coupled into flip-flops E_0 and E_1.
2. Since E_0 is already set, no change in this flip-flop occurs.
3. The resistor control gate of flip-flop E_1, which was enabled when E_0 was set, allows the echo pulse to reset flip-flop E_1.
4. The resetting of E_1 disables G. P. G. #1, and the forward counting into Register #1 is stopped with the contents at $f_m t_1 = A$.

For the time encoding of the fixed distance d, the following occurs:

1. The echo from the reflection plate is amplified, squared, and coupled into flip-flop E_2.
2. Since the reset inhibit signal is not present, flip-flop E_2

is reset.

3. This resetting disables G. P. G. #2, and the forward counting in Register #3 is stopped with the contents at $f_m t_2 = B$.

The characteristics of the receiving equipment time delays can now be discussed. The amplifiers and Schmitt triggers possess time delays which could adversely affect the encoding of times t_1 and t_2. For example, if the digital ultrasonic start signal was applied to the G. P. G. gates directly, then the times encoded would be in error by the time delay of the echo travelling through the amplifier and Schmitt trigger combination. To avoid this encoding error, the start signal and the echo traverse the same amplifier and Schmitt trigger path.

Calculation Operation

The calculation operation of the digital transducer accepts the time encoding information in Registers #1 and #3 and performs the calculation in three steps. These are read-in, count-down, and zero detection. Figure 10 presents the implementation of these three steps. The read-in step results in loading the count of $f_m t_1$, which is in Register #1, into the backward counting Register #2. This is accomplished as follows:

1. At some time prior to read-in, all of the flip-flops of Register #2 are set. For simplification purposes, suppose Register #2 contained four binary bits rather than twelve. Thus it would possess the full count of 1111, which is

decimal 15.

2. For read-in, if Register #1 contained the count of decimal 10, which is binary 1010, it is necessary to reset the 2^0 and 2^2 binary bits of Register #2.

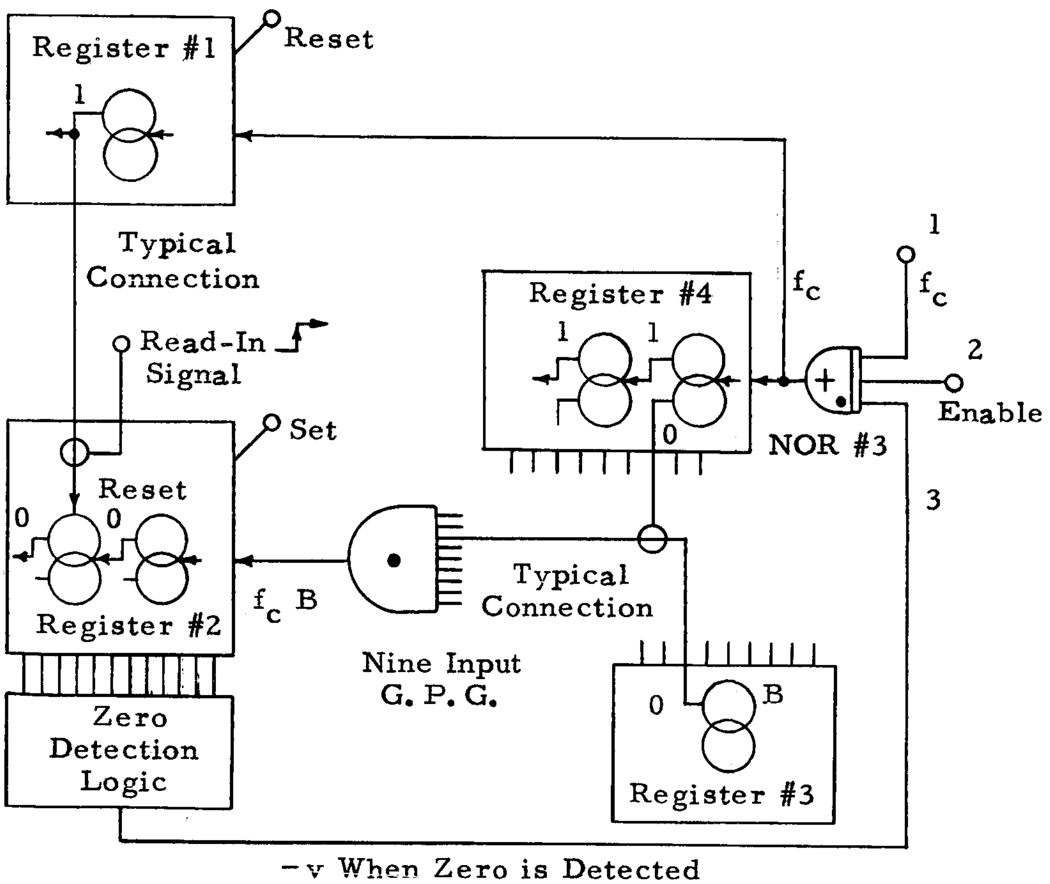


Figure 10. Calculation Implementation

3. Since the 1 Outputs of the flip-flops in Register #1 are used as control levels in Register #2, then applying the read-in signal will result in resetting only those flip-flops of Register #2 which correspond to those in Register #1 which are reset. Further, the resetting of flip-flops in Register #2 will not result in transition propagation to

more significant stages, since the counter counts backward.

4. Register #2 now contains count total A, and the calculation of A/B can proceed.

The count-down step utilizes the operational multiplier to obtain the ratio A/B. Since Register #1 functions as a forward counter during both the measurement and calculation operations, it must be reset prior to the initiation of the count-down pulses to Register #2. When NOR #3 receives the enable (0 volt) signal on terminal #2, the following occurs:

1. Since Register #2 is not zero, the pulse train on terminal #1 of NOR #3 appears at its output.
2. This frequency, f_c, is directed to Register #1 and to the operational multiplier as prescribed in the Transducer Implementation Equation section of Chapter II.
3. The operational multiplier modifies f_c by the numeric B and provides an output frequency of f_c B to the backward counter, Register #2.
4. Pulses continue to enter Register #1 and the operational multiplier until Register #2 becomes zero.

The zero detection step includes the following:

1. As long as terminals #2 and #3 are at 0 volts, the pulses continue to appear on the output of NOR #3.
2. The pulses are inhibited when the zero detection logic of Register #2 causes terminal #3 of NOR #3 to go to the

negative potential.

3. The count, which Register #1 now contains, represents the temperature compensated absolute binary measurement of the depth.

The logical implementations of Registers #1, #2, #3, and #4 are presented in Figures 11, 12, 13, and 14, respectively. Register #1 possesses, not only the ability to count forward at the frequencies of f_c and f_m, but also the ability to shift out the depth measurement most significant bit or least significant bit first. For these shifting operations, the trigger inhibit input is used to avoid flip-flop state changes when positive going voltage transitions occur at the T inputs. Register #2 possesses, not only a Base Resistor Set, which is used in the calculation operation, but also a manual Emitter Reset. After the equipment is turned on, but before the first operation cycle, this Emitter Reset is used to insure that Register #2 contains zero and that NOR #3 is inhibited. Registers #3 and #4 differ only in the speed of the logic which is used.

The control of the measurement and calculation operations is the function of the control or timing logic. The next section will present the gated timing solution and the complete logical implementation of the digital transducer.

Timing Operation

The transducer timing is synthesized by explicitely defining, with respect to time, the exact operations which must be performed

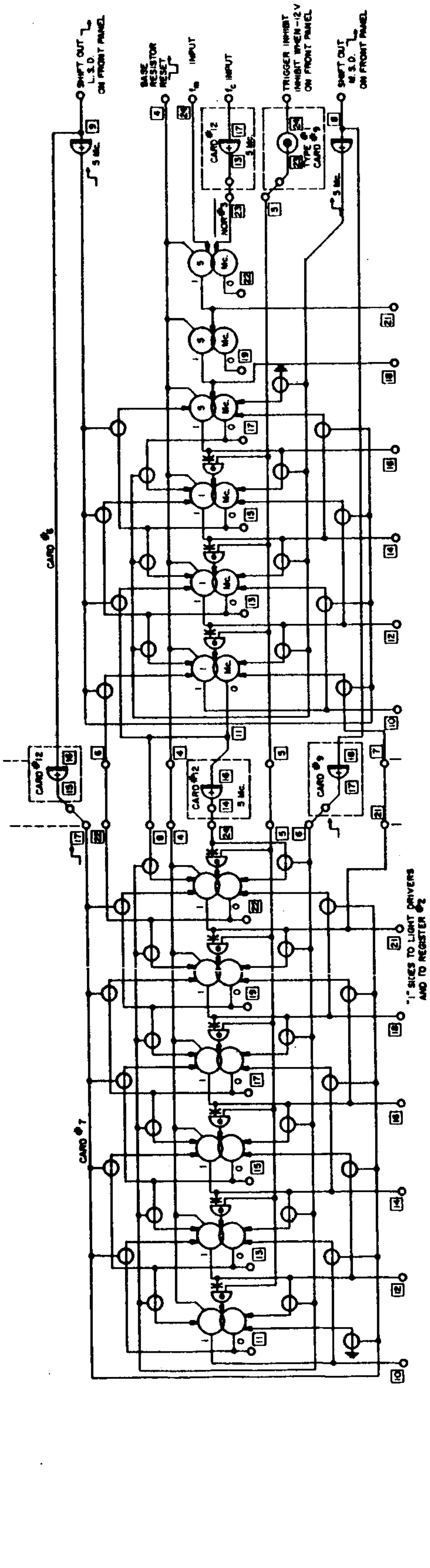


FIGURE 11. REGISTER #1 IMPLEMENTATION

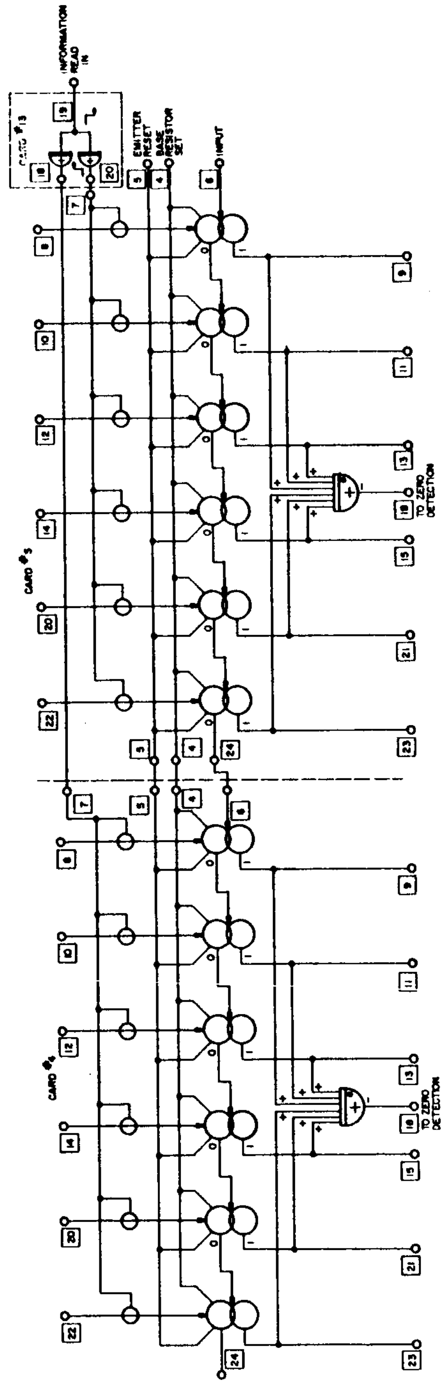


FIGURE 12. REGISTER #2 IMPLEMENTATION

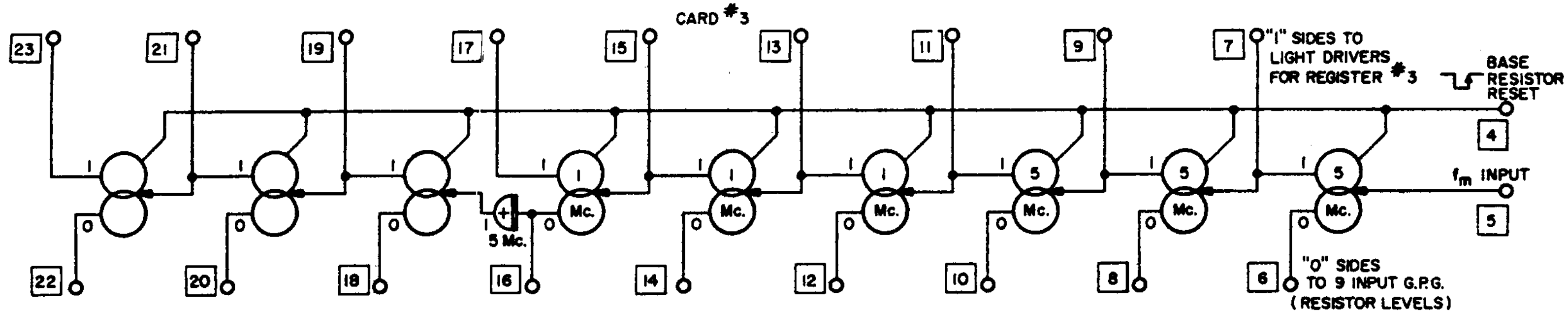


FIGURE 13. REGISTER #3 IMPLEMENTATION

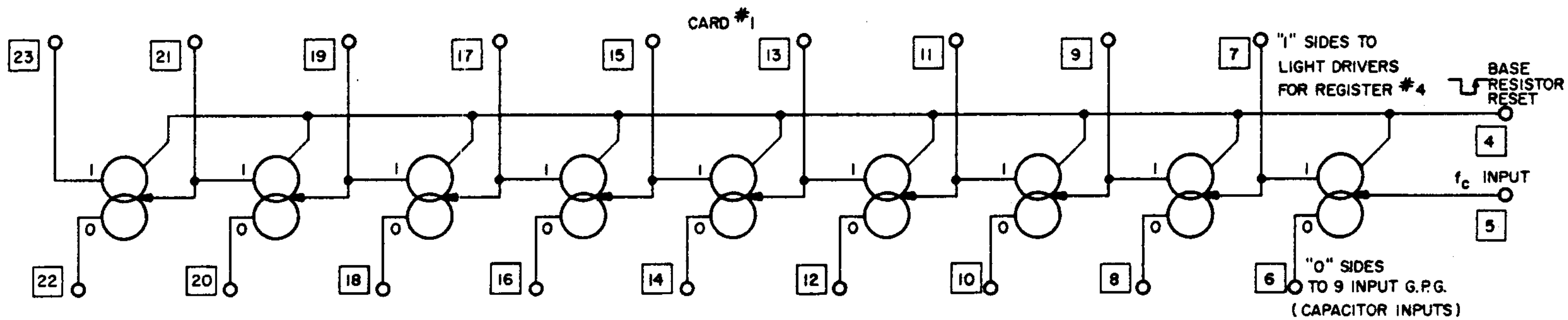


FIGURE 14. REGISTER #4 IMPLEMENTATION

to enable the transducer to complete an operation cycle. By equating this sequential list to the count sequence of the timing counter, the timing will be determined; and the logical equations for the timing gates can be written. The calculation frequency, f_c = 20 kc./sec., is used for the calculation operation and for the timing system. By having one clock to perform the two functions, the need for a second clock was removed.

The transducer timing counter consists of a 5 bit forward counting binary counter, which is designated as flip-flops A through E. For an input frequency of 20 kc./sec., each count corresponds to 50 μsec. For timing operations of 100 μsec. duration, only flip-flops A through D are involved. Table 2 presents the sequential list of transducer operations, the timing counter count, and the logical equations which are necessary to produce the operations.

Operation	Timing Counter Count Dec.	Binary ABCD.E	Time in μsec.	Function
System Ready	15	1111		NAND #1 = (Zero Detection)$\cdot$(Start Signal)
Start Operation Signal 1. Enable counter to count 14. 2. Reset F.F. E_0	0	0000	0	NOR #1 = $\bar{A}+\bar{B}+\bar{C}$ Transition used
No Operation	1	0001	100	
Initialize System Reset Registers #1, #3, #4; Set Register #2; Set F.F. E_1 & E_2.	2	0010	200	NOR #2 = $\bar{A}\bar{B}C\bar{D}$

Table 2. Timing Statements (continued)

Operation	Timing Counter Count Dec.	Binary	Time in μsec.	Function
		ABCD.E		
No Operation	3.0	0011.0	300	
Generate Ultrasonics 1. Signal packet 2. Inhibit reset of F.F. E_2.	3.5	0011.1	350	NAND#2 = $\bar{A}\bar{B}CDE$ P.G. #3 (0.72 μsec.) P.G. #6 (21 μsec.)
This provides measurement time of	4	0100	400	
950 μsec.	5	0101	500	
	6	0110	600	
	7	0111	700	
	8	1000	800	
	9	1001	900	
	10	1010	1000	
	11	1011	1100	
	12	1100	1200	
Read f_m t_1 into Register #2 by trailing edge at 1296.8 μsec.	12.5	1100.1	1250	NAND #3 = $AB\bar{C}\bar{D}E$
Reset Register #1	13	1101	1300	NOR #4 = $AB\bar{C}D$
Enable Calculation until Register #2 contains zero.	14	1110	1400	NAND #4 = $ABC\bar{D}$
Pulses for Calculation. Maximum time available for calculation is 0.2 sec.				NOR #3 = (Pulses, f_c)$\cdot$ (NAND #4)$\cdot$ $\overline{\text{(Zero Detection)}}$
System Ready	15	1111		NAND #1 = (Zero Detection)$\cdot$ (Start Signal)

Table 2. Timing Statements

The combining of the implemented timing statement with the measurement and calculation implementations results in the complete logical statement of the Digital Liquid Level Transducer. This is presented by Figure 15. As a supplement to this logical implementation, Figure 16 presents the transducer timing diagram.

To illustrate how these figures define, both in circuit modules and in time, the operation of the transducer, the operations which occur at count 3.5 will be discussed. Table 2 defines count 3.5 to be used for the generation of the ultrasonic signals. Thus the action of NAND #2 is presented on the timing diagram at count 3.5. The signal packet is enabled by pulse generator #3 (P. G. #3), as is presented in the next entry of the timing diagram. The following observations can be noted from other entries in the timing diagram. The signal packet, which is the output of G. P. G. #4, drives both ultrasonic pulse generators. The generators drive the sound projectors, and the amplifiers and Schmitt triggers transfer this start counting information to flip-flops E_0 and E_2. Flip-flop E_0 is set, and the counting to Registers #1 and #3 is enabled by G. P. G. #1 and #2 enable gates. Because P. G. #6 provides a reset inhibit signal, flip-flop E_2 does not change state. The preceding timing at count 3.5 can be followed logically also in Figure 15.

Operation Variations

The function of the manual switches which are presented in the logical implementation will now be discussed.

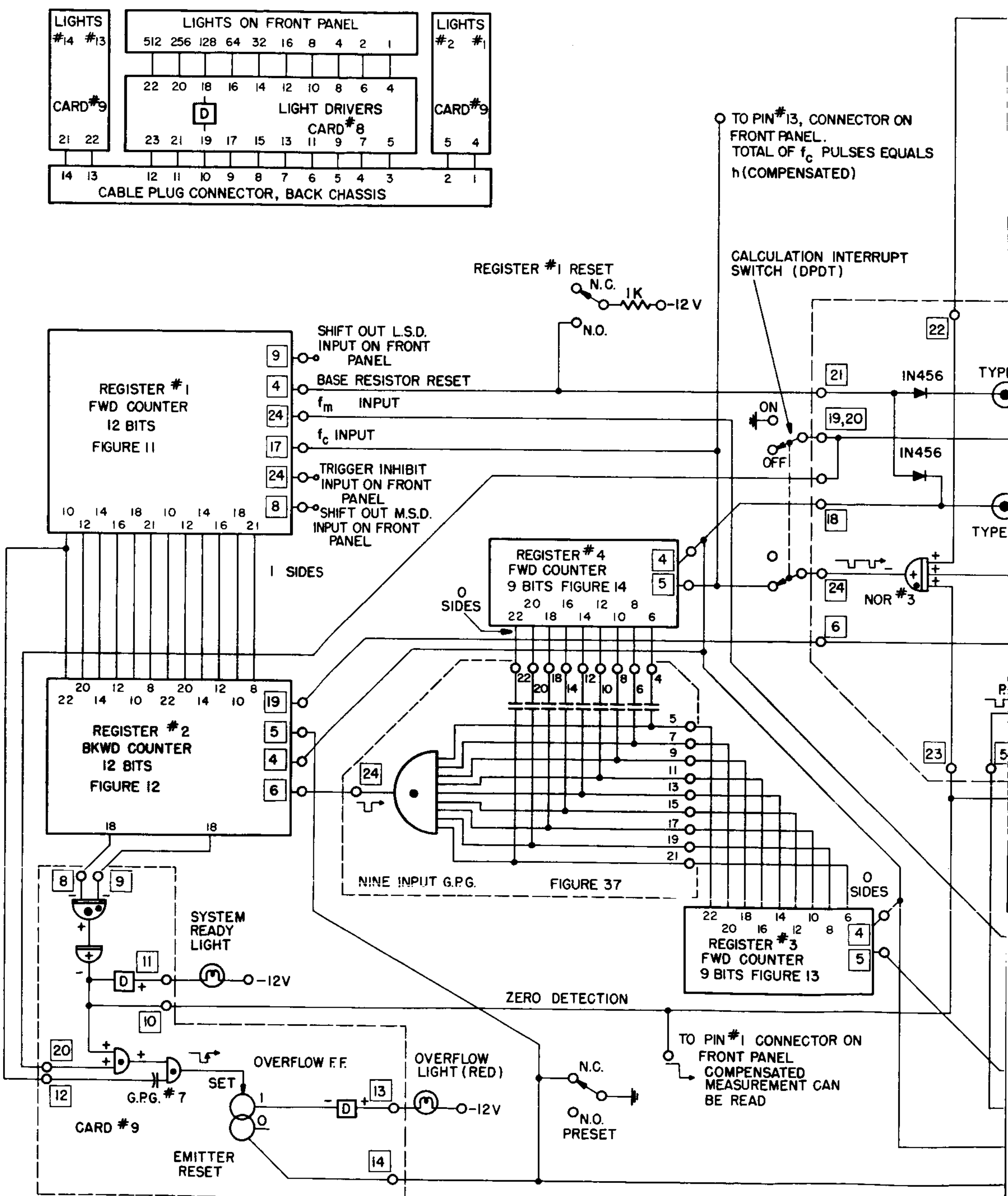
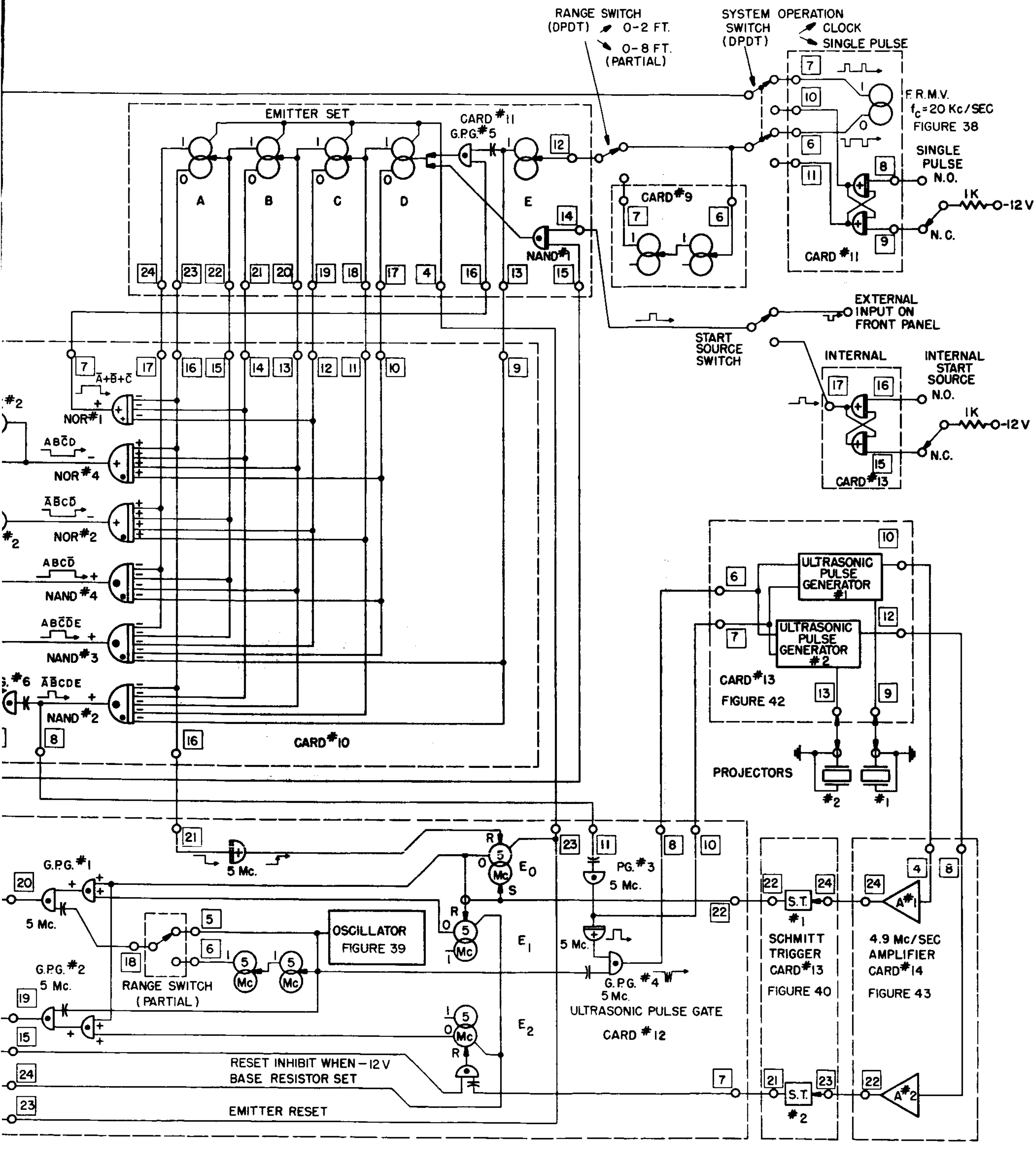


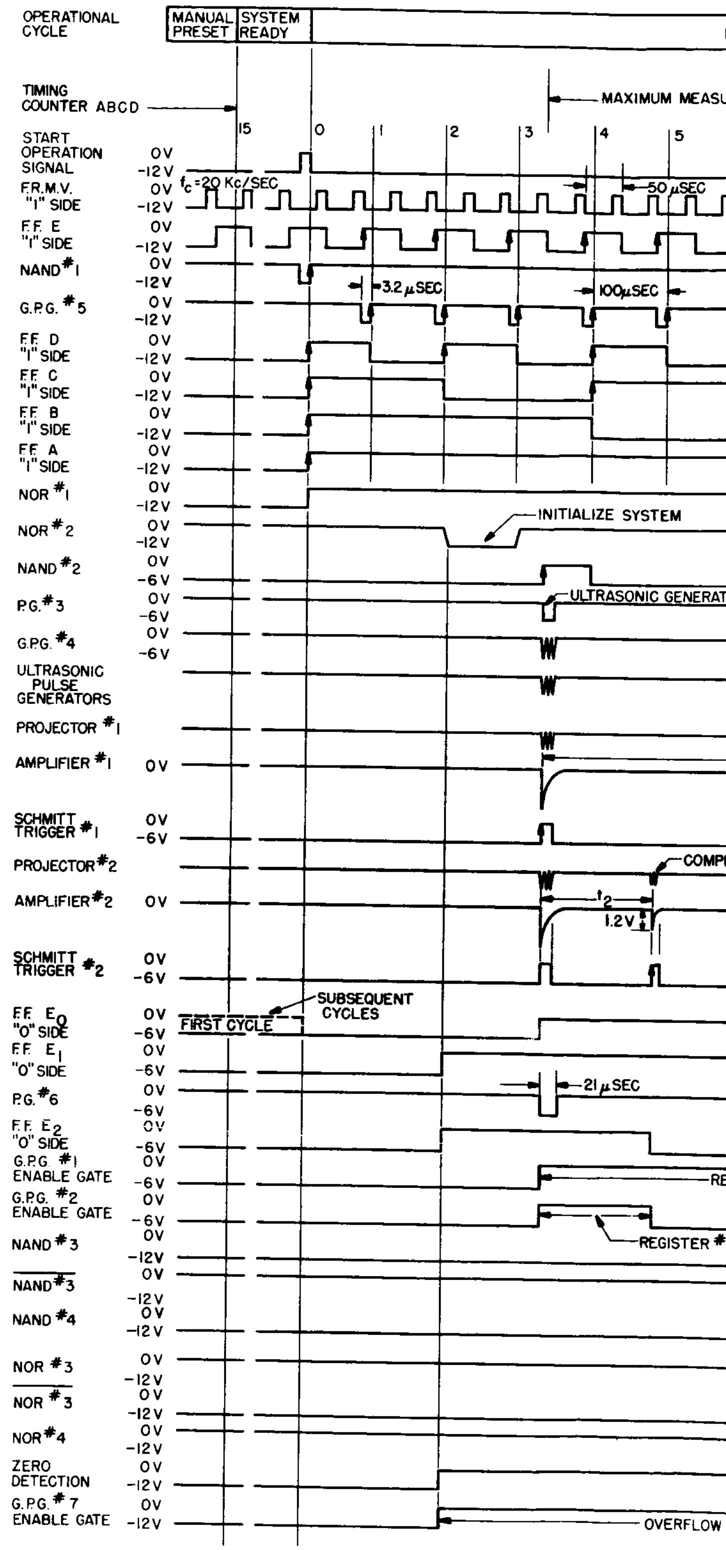
FIGURE 15. DIGITAL

58-0



TRANSDUCER LOGICAL IMPLEMENTATION

58 - 2


OPERATIONAL CYCLE
MANUAL PRESET
SYSTEM READY
TIMING COUNTER ABCD
MAXIMUM MEASU
15
0
1
2
3
4
5
START OPERATION SIGNAL
F.R.M.V. "1" SIDE
f_c=20 Kc/SEC
50 μSEC
F.F. E "1" SIDE
NAND #1
3.2 μSEC
100μSEC
G.P.G. #5
F.F. D "1" SIDE
F.F. C "1" SIDE
F.F. B "1" SIDE
F.F. A "1" SIDE
NOR #1
NOR #2
INITIALIZE SYSTEM
NAND #2
P.G. #3
ULTRASONIC GENERAT
G.P.G. #4
ULTRASONIC PULSE GENERATORS
PROJECTOR #1
AMPLIFIER #1
SCHMITT TRIGGER #1
PROJECTOR #2
COMP
AMPLIFIER #2
t_2
1.2V
SCHMITT TRIGGER #2
F.F. E_0 "0" SIDE
FIRST CYCLE
SUBSEQUENT CYCLES
F.F. E_1 "0" SIDE
P.G. #6
21 μSEC
F.F. E_2 "0" SIDE
G.P.G. #1 ENABLE GATE
RE
G.P.G. #2 ENABLE GATE
REGISTER #
NAND #3
$\overline{NAND \#3}$
NAND #4
NOR #3
$\overline{NOR \#3}$
NOR #4
ZERO DETECTION
G.P.G. #7 ENABLE GATE
OVERFLOW
0V
-12V
-6V

59

①

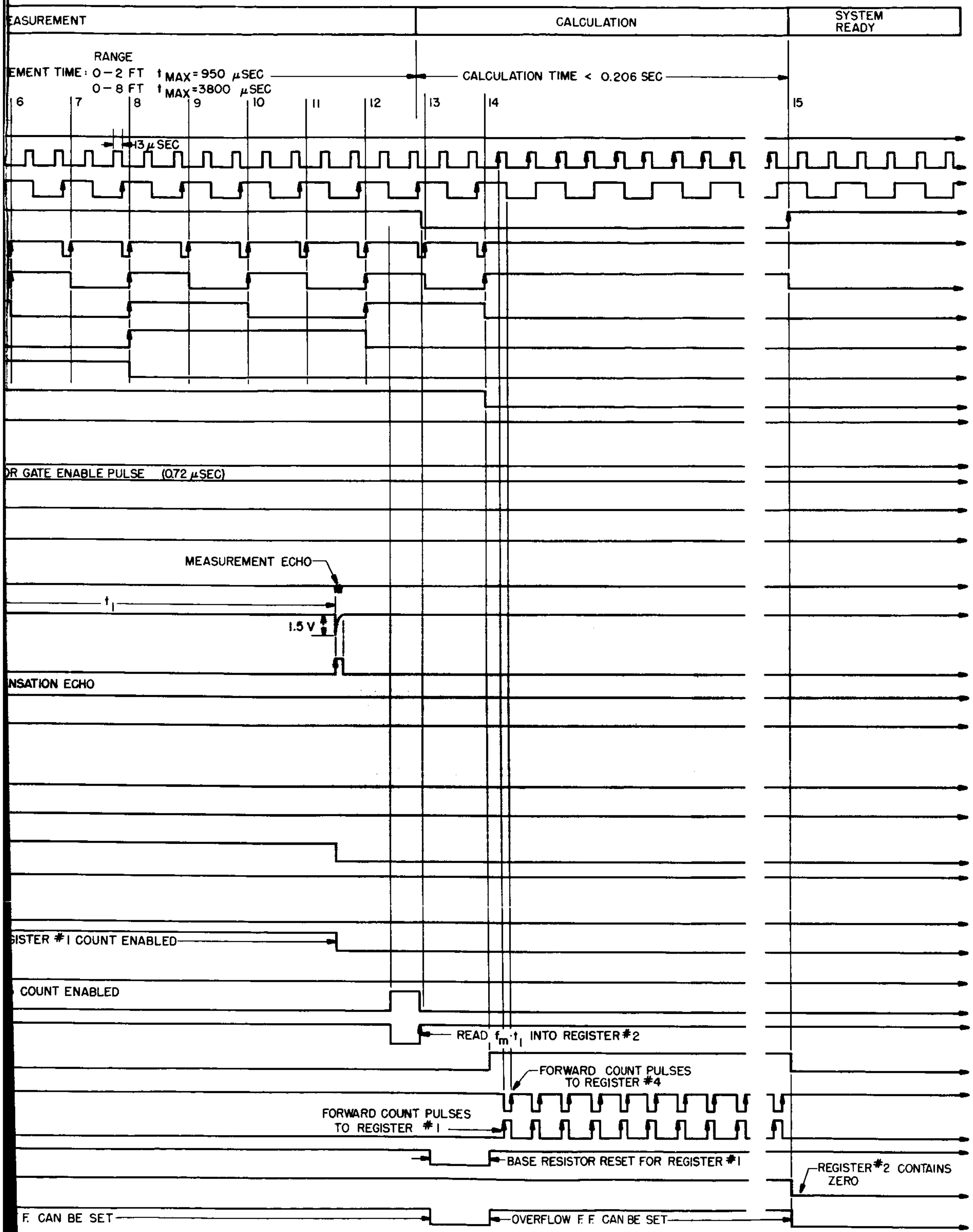


FIGURE 16. DIGITAL TRANSDUCER TIMING DIAGRAM

59

2

PRESET Switch (Location: lower left quadrant of Figure 15). The PRESET switch is used only after equipment has been turned on. Its function is to reset the flip-flops E_0, A, B, C, D, and Overflow and to reset the flip-flops of Register #2. It is imperative that states of these control and measurement memory devices be determined for correct operation of the transducer to result. If at some later time the count capacity of Register #1 is exceeded, the Overflow flip-flop will be set, and the Overflow Light will come on. To restore normal operation, the PRESET switch will be depressed and released.

START SOURCE Switch (Location: upper right quadrant). The START SOURCE switch enables the use of an internal or an external start source. For operation of the transducer by itself, the internal start source will be used.

INTERNAL START SOURCE Switch (Location: upper right quadrant). The INTERNAL START SOURCE switch enables the complete operation of the digital transducer without the use of circuits which are external to the transducer.

SYSTEM OPERATION Switch (Location: upper right quadrant). The SYSTEM OPERATION switch provides a choice of clock and single pulse operation.

SINGLE PULSE Switch (Location: upper right quadrant). The SINGLE PULSE switch enables the measurement and calculation operations to be sequenced slowly in time for indicator light verification of correct operation.

RANGE Switch (Locations: upper and lower right quadrants). The RANGE switch makes the digital system capable of measuring maximum water depths of 2 and 8 feet.

CALCULATION INTERRUPT Switch (Location: upper left quadrant). The CALCULATION INTERRUPT switch enables the operation of the transducer to be stopped just after the time encodings have been completed. At this time counts $f_m t_1$ and $f_m t_2$ can be read in their respective registers by the use of the indicator lights.

REGISTER #1 RESET Switch (Location: upper left quadrant). The REGISTER #1 RESET switch provides a manual means for a resetting Register #1 when the CALCULATION INTERRUPT switch is on. Then by switching the INTERRUPT switch to off, the calculation operation will occur.

Transducer Implementation

The construction of the digital transducer involves the concept of function modules. These are sub-systems of the transducer whose circuit actions are so closely related that their adjacent physical location is desirable. Figure 15, which presents the logical implementation, also indicates these function modules. Each function module has been constructed using discrete components on an individual printed circuit card which measures 5" x 7 1/2". Fourteen cards are required for the transducer. The boxed numbers associated with the interconnections of the various cards indicate the terminals of each card which are used. The amount of logic which is found on each card is determined by the availability of unused terminals and unused card space. By using connectors which have 24 terminals, it is possible to get complete registers (Registers #3 and #4) on individual printed circuit cards.

Figures 17 and 18 present the front and back views of the instrument, respectively. The front view illustrates two items which have not been previously discussed. First, the connector in the lower center of the panel provides both the 0 and 1 side Outputs for the 10 higher order flip-flops of Register #1. Thus the compensated level measurement can be read into other digital equipment in a parallel form. By using only the most significant and least significant bit outputs, serial read-out is available. Second, the lights which indicate the level measurement are also only 10 in number. These correspond to the 10 higher order flip-flops of Register #1. To check operation of the entire 12 bits of the register, the lights for the two least significant bits are located on printed circuit card #9. These can be seen in the picture along the top of the card near the back of the instrument.

The back view of the instrument further illustrates a construction feature. The four connectors, which are located near the center, provide one with the capability of visually checking the oper-

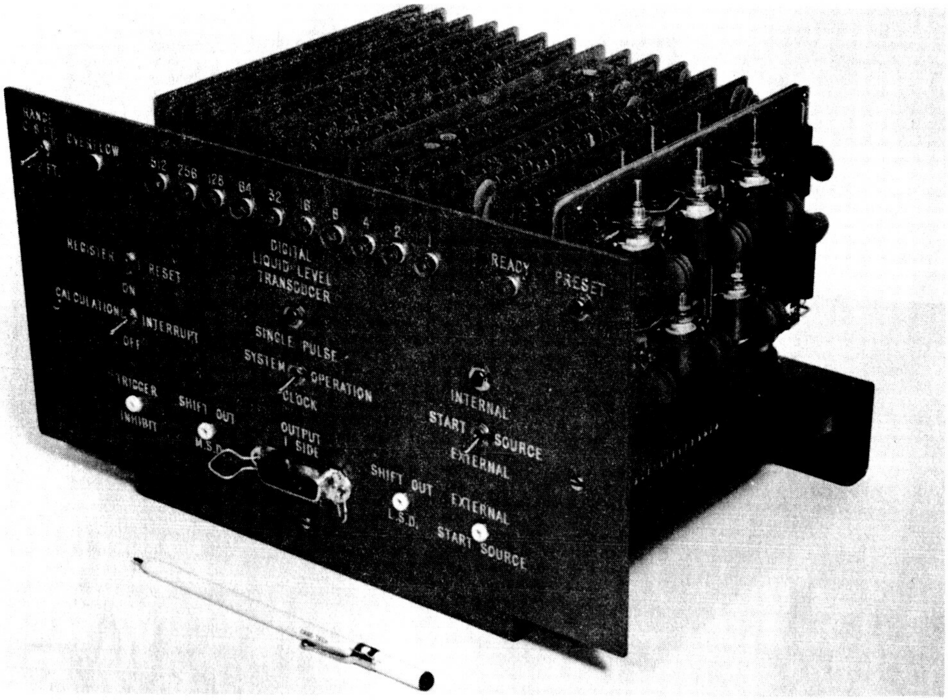


Figure 17. Digital Transducer, Front View

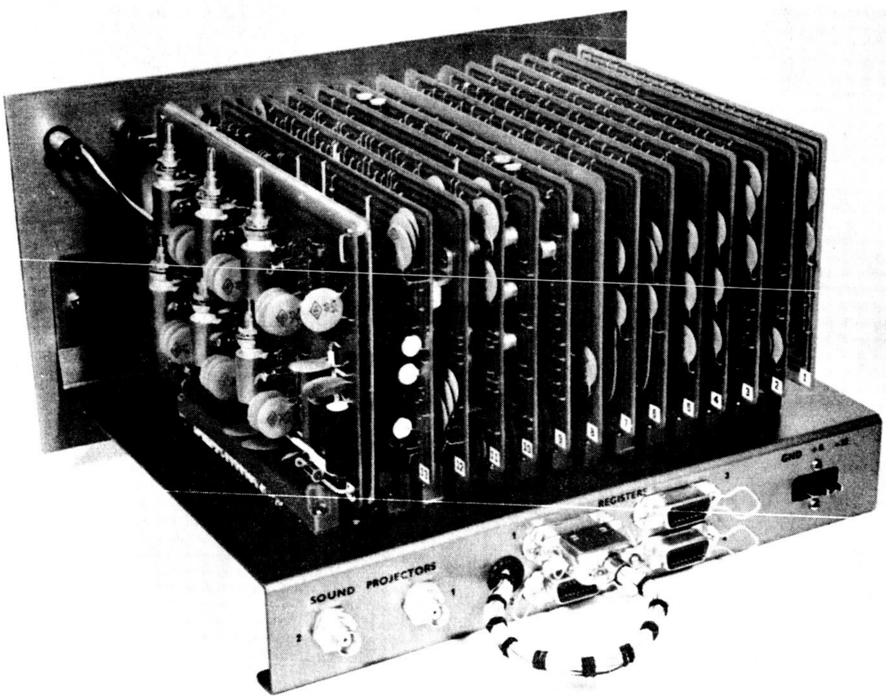


Figure 18. Digital Transducer, Back View

ation of Registers #1 through #4 by observing the indicator lights on the front panel. The observation of the timing counter, in addition to the observation of Register #4, is possible when the plug is attached to the Register #4 connector. In every case, the two least significant lights for the two least significant flip-flops of the register being observed are on card #9 near the back of the instrument. The two lights on card #9 near the front of the instrument are used to observe flip-flops A and B in the timing counter.

Figures 19 through 22 illustrate various digital transducer printed circuit cards. Figure 19 presents Register #3, which is used for the high speed encoding of time, t_2. Figure 20 illustrates the oscillator and the 5 Mc./sec. control logic which form card #12. Figure 21 presents the Schmitt trigger and ultrasonic pulse generator circuits. Finally, Figure 22 shows the component layout of the two 4.9 Mc./sec. amplifiers.

The ultrasonic projectors and the echo reflection plate are illustrated in Figure 23. By using the mounting arrangement which is shown, it was possible to remove the projector assembly from the water when measurements were not desired. Thus physical attachment of the projector assembly to the tank was avoided.

Figure 24 presents the Digital Liquid Level Transducer in its protective enclosure.

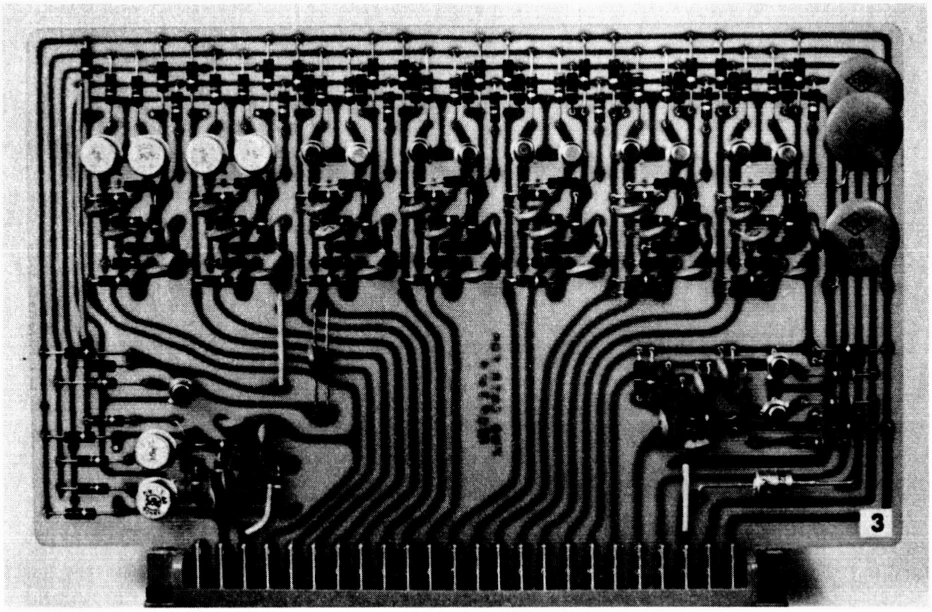


Figure 19. Register #3

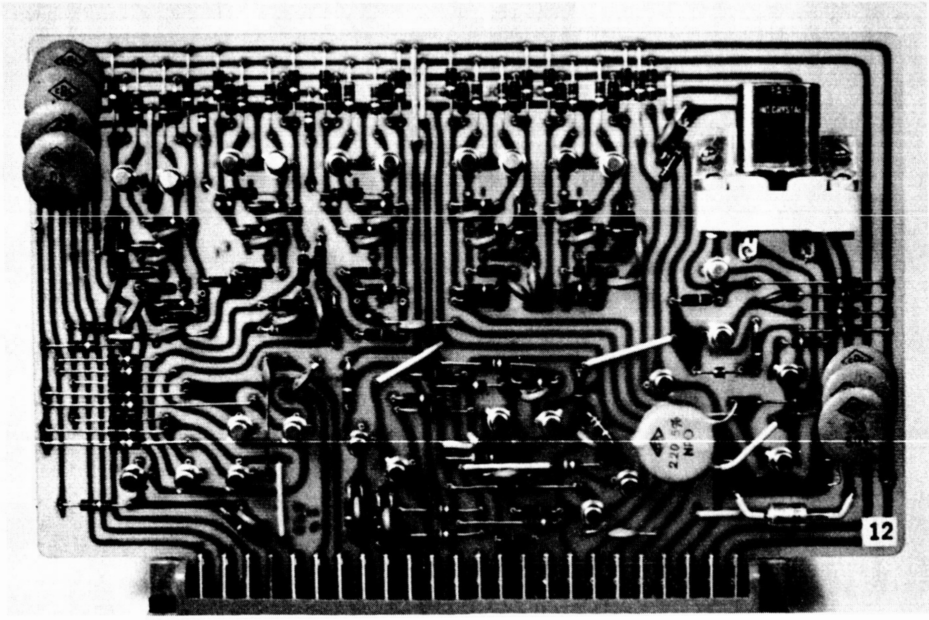


Figure 20. Oscillator and 5 Mc./sec. Control Logic

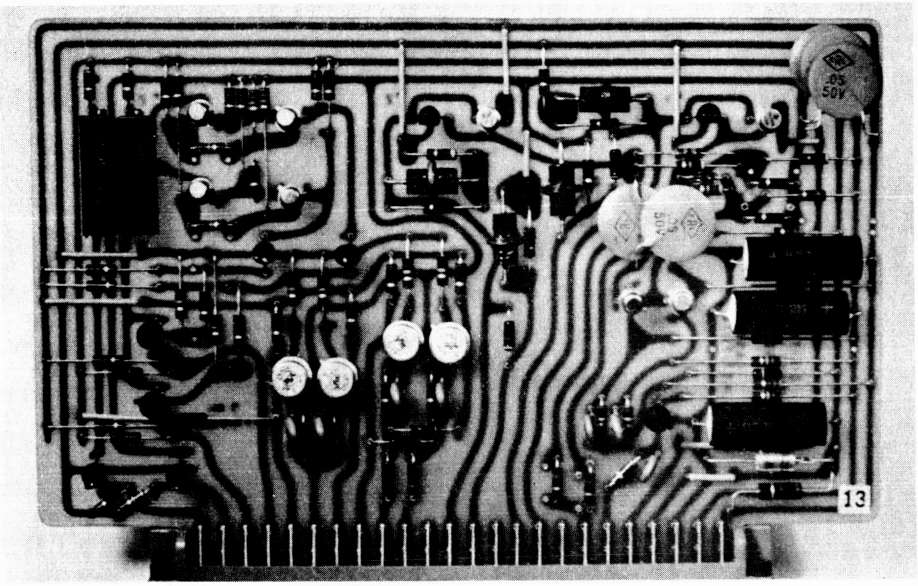


Figure 21. Schmitt Triggers and Ultrasonic Pulse Generators

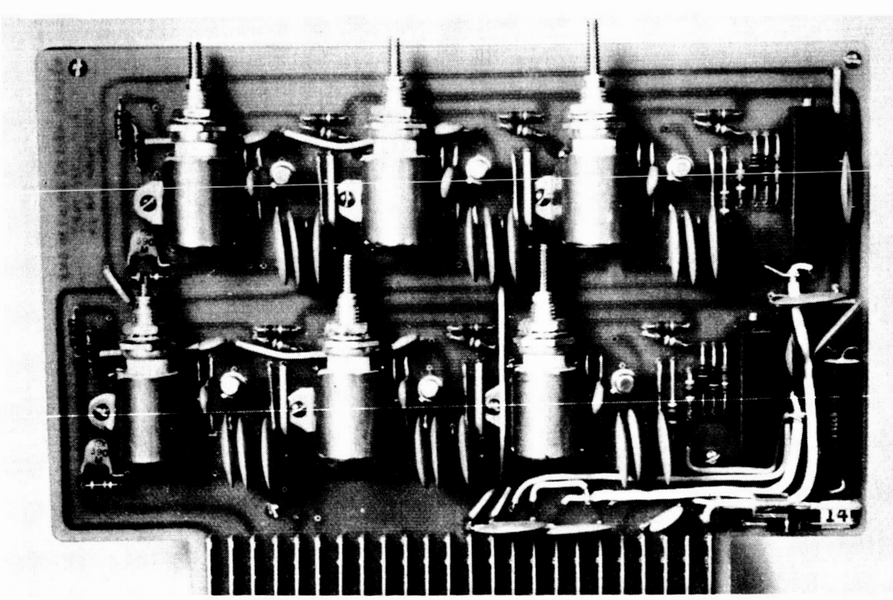


Figure 22. Amplifiers, 4.9 Mc./sec.

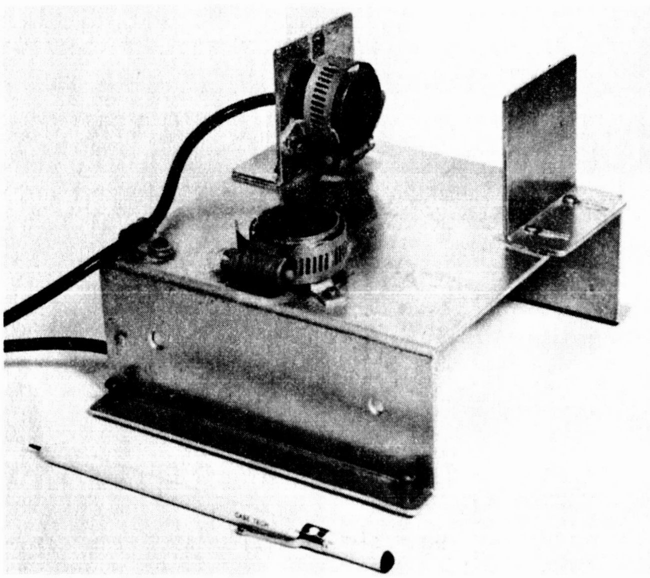


Figure 23. Ultrasonic Projector Assembly

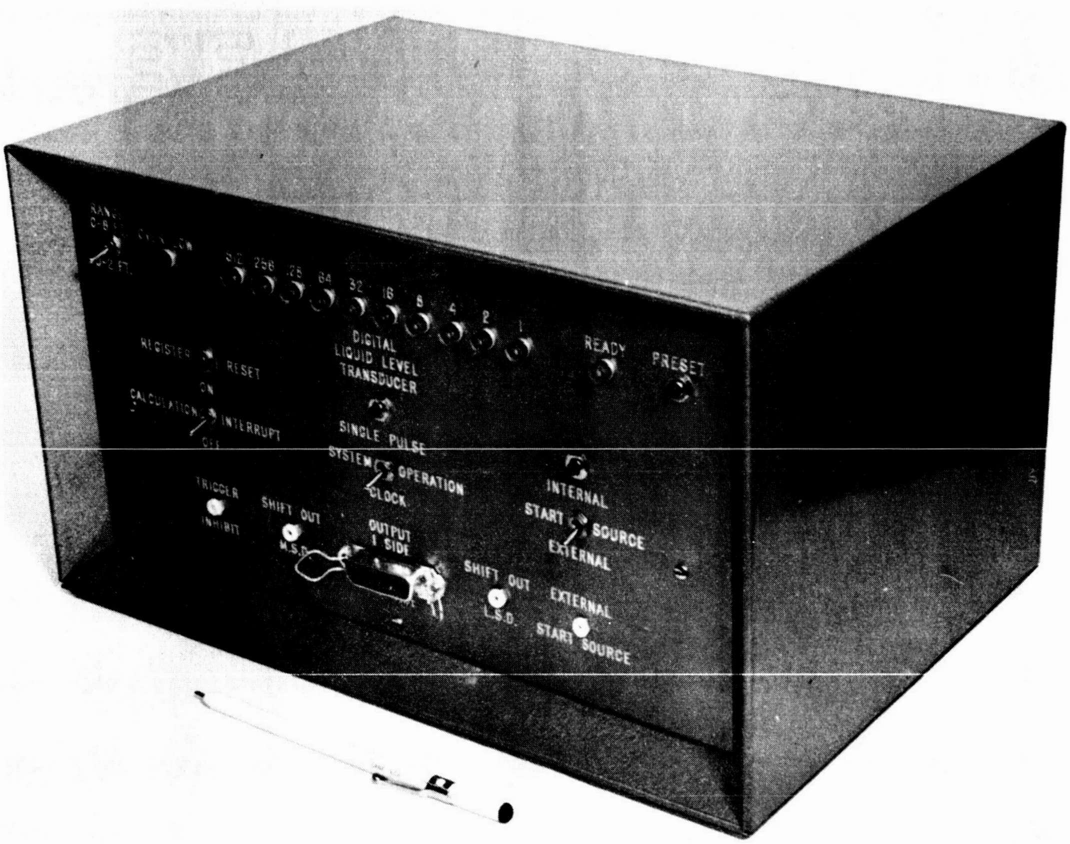


Figure 24. Digital Liquid Level Transducer

CHAPTER IV

RESULTS OF TESTS

Water Temperature Variation

The temperature variation tests were conducted to observe the effect of water temperature on the compensated digital measurement of height. These tests were performed by heating the water in the 55 gallon test tank with three electric emersion heaters. To provide a uniform temperature throughout, a small stirring motor was used. Measurements were made with the stirring motor running. This resulted in surface ripples. The water temperature was obtained by using copper-constantan thermocouples. The reference junction of 32°F was established by using an ice and water mixture.

Two temperature variation tests were conducted. They differ in two items. First, the fixed distance d was readjusted for the second test. By this action, the requirement of establishing d at the temperature extreme which results in the lower velocity of propagation could be illustrated. Second, the tests differ in the amount of water which was measured. Test #1, which was for the greater depth, required about 5 1/2 hours to complete. Test #2, which obtained the measurements for approximately the same temperature range, required about half as long. Figure 25 presents the temperature variation test results. In addition to the compensated digital measurement h, the $(f_m t_1)/4$ and $(f_m t_2)/4$ counts are

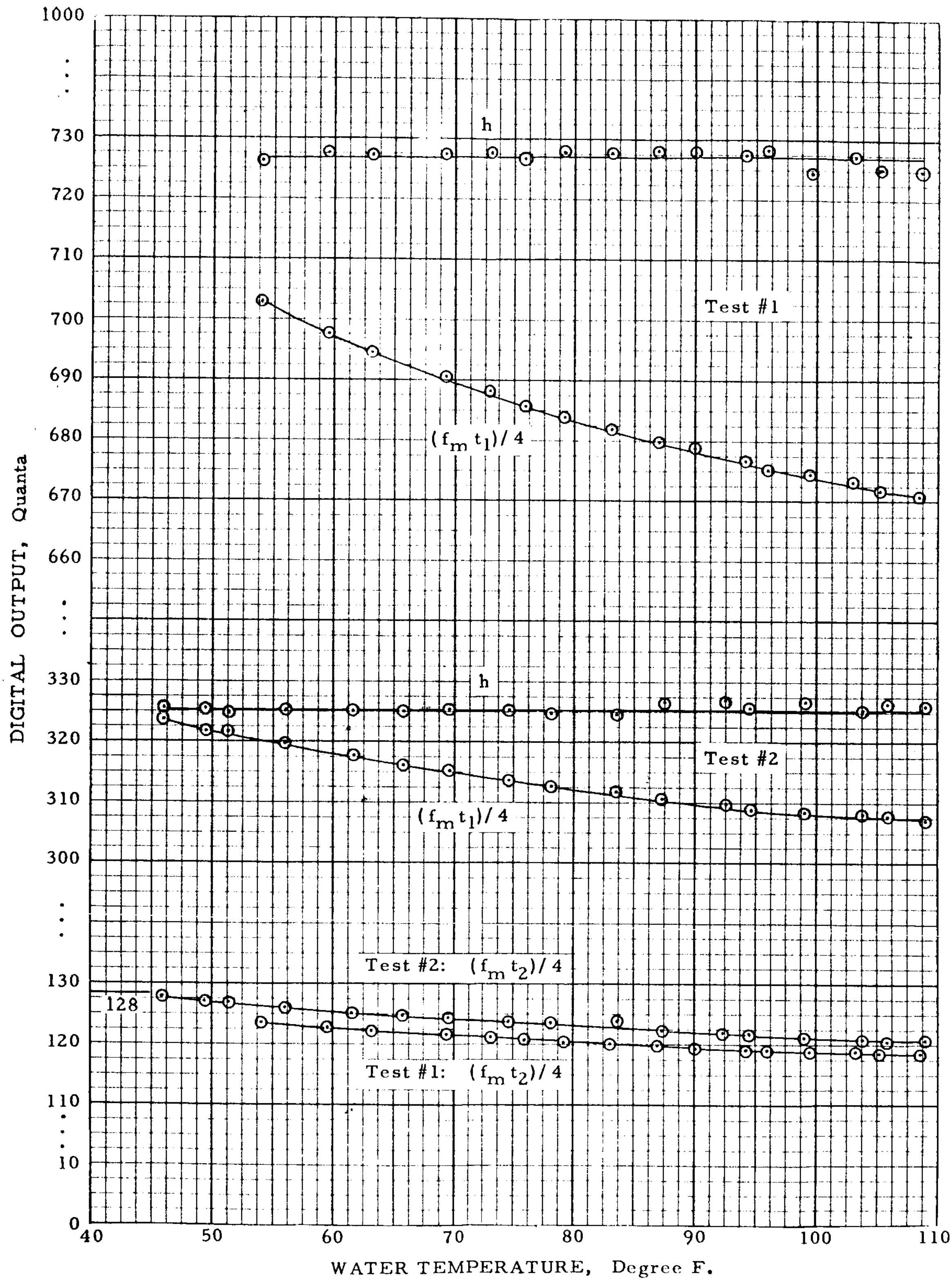


Figure 25. Water Temperature Variation Tests

presented for each test. By presenting these time encoding counts divided by 4, one can observe the uncompensated height measurement and the distance d measurement in terms of the output quantization.

The system measurement accuracy for each test can be obtained by noting the two extreme values of the compensated digital measurement. Also the average compensated digital measurement can be computed for each test. By finding the largest difference between one of the extreme digital measurements and the average of the digital measurements, the system accuracy can be computed. Table 3 presents the system accuracies which are computed for tests #1 and #2.

Compensated h, quanta	Test #1	Test #2
Maximum	728	327
Minimum	723	324
Average of all h, quanta	726.2	325.4
Largest difference (Δh), quanta	−3.2	+1.6
h_{max}, quanta	1000	1000
System Accuracy (worst case)	$\frac{-3.2}{1000}$ (100%)	$+\frac{1.6}{1000}$ (100%)
or	±0.32%	±0.16%

Table 3. System Accuracy with Surface Ripples

After the completion of test #2, the stirring motor and heaters were turned off; and ten consecutive compensated height measurements were made. The water surface was smooth. Table 4 contains these results along with the system accuracy calculation.

Compensated h, quanta	Test #2 (Smooth surface)
Maximum	326
Minimum	324
Average of all h, quanta	324.6
Largest difference (Δh), quanta	+ 1.4
Smallest difference (Δh), quanta	− 0.6
h_{max}, quanta	1000
System Accuracy	+0.14% to −0.06% of the full range.

Table 4. System Accuracy with Smooth Surface

The system accuracy of the conventional ultrasonic device is based on the difference between the uncompensated and the average compensated height measurements at the highest temperature extreme. Table 5 presents the uncompensated system accuracy for both tests. The poorest conventional ultrasonic system accuracy results from the maximum depth measurement at the maximum water temperature. This, however, is not presented in Table 5.

Measurement Frequency Variation

The frequency variation test was performed by observing the compensated and uncompensated digital measurement values for four different measurement count frequencies. The water surface was smooth, and temperature was constant for the test. Table 6 presents the digital values.

	Test #1	Test #2
Uncompensated h, quanta	670	307
Avg. compensated h, quanta	726.2	325.4
h_{max}, quanta	1000	1000
Difference (Δh), quanta	-56.2	-18
Uncompensated System Accuracy	$\frac{-56.2}{1000}$ (100%)	$\frac{-18}{1000}$ (100%)
or	-5.62%	-1.8%

Table 5. Conventional Ultrasonic System Accuracy

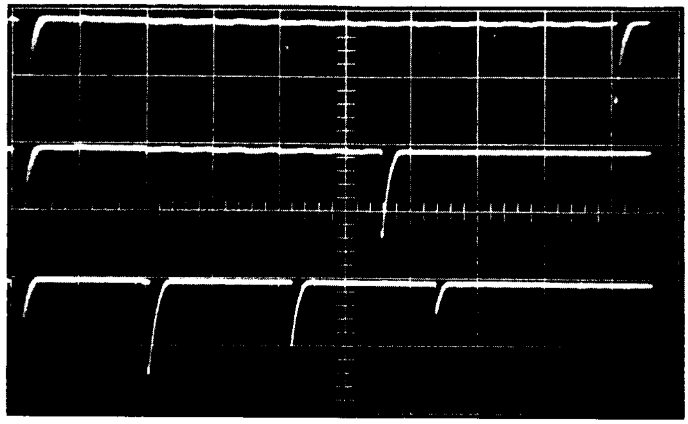
Frequency, f_m in Mc./sec.	$(f_m t_1)/4$ in quanta	$(f_m t_2)/4$ in quanta	Compensated Measurement, h, in quanta.
4.380	507.75	106.50	610.25
4.400	510.50	107.00	610.50
4.950	574.50	120.50	610.00
5.000	580.25	121.50	610.50

Table 6. Measurement Frequency Variation

Range Addition

The 0 - 8 ft. range was added to the logical implementation of the digital transducer in order to make the instrument useful for other measurement applications. For the 0 - 8 ft. range, the maximum output quanta count remains at 1000, while each quantum now represents 4(0.002 ft.). Since the 55 gallon tank test facility limited the depth measurement to approximately 2 1/2 ft., measurements approaching the 8 ft. range were not possible. The capability of measurement to this limit will depend upon the ultrasonic considerations of projector signal strength, signal attenuation, and amplifier sensitivity.

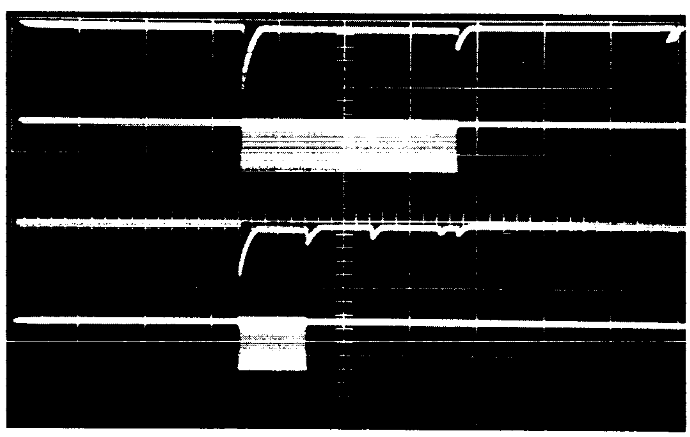
To study the range capability of the ultrasonic equipment, a propagation loss test was devised. This test enabled the echo strength to be observed for three depths within the 2 1/2 ft. limitation. The water temperature remained constant throughout the test. Figure 26 presents oscilloscope traces of the signals at the output of amplifier #1. The top oscilloscope trace presents the -1.18 volt echo which results from a propagation wave travel time of 900 μsec. The initial ultrasonic drive pulses are on the far left of each trace. After removing some water from the tank, the middle trace and an echo of -1.29 volts at 560 μsec. was obtained. Finally, after decreasing the depth still further, the bottom trace and a first echo of -1.41 volts at 207 μsec. was obtained. The second and third echos on the bottom trace represent additional round trips by the ultrasonic pulse between the sound projector and the surface. Now



Horizontal:
100 μ sec. /cm.

Vertical:
1 volt/cm.

Figure 26. First Echo Voltages



Horizontal:
100 μ sec. /cm.

Vertical:
Amplifiers #1 and #2:
5 volts/cm.
G.P.G. #1 and #2:
10 volts/cm.

Figure 27. Measurement Range: 0 - 2 ft.

by using the first echo of the bottom trace as a reference, both for voltage and time, one can form the following ratios for the other two first echos.

Time Ratio	Echo Voltage Ratio
$\dfrac{(560 - 207)\ \mu\text{sec.}}{(900 - 207)\ \mu\text{sec.}}$	$\dfrac{-(1.29 - 1.41)\ \text{v}}{-(1.18 - 1.41)\ \text{v}}$

or 0.51 0.52

The fact that these ratios of time and voltage are approximately equal will allow one to extrapolate to the depth to which the digital transducer is capable of measuring. Since the Schmitt triggers have upset voltages of -0.5 volts, a returning echo, after amplification, must have at least a magnitude of -0.5 volts for correct operation of the digital equipment. For a conservative estimate of measurement depth, an amplified echo voltage of -0.75 volts will be used. The time which corresponds to twice the maximum measurement depth will be called t. Applying the time and voltage ratios, one obtains the following:

$$\frac{(t - 207)\ \mu\text{sec.}}{(900 - 207)\ \mu\text{sec.}} = \frac{-(0.75 - 1.41)\text{v}}{-(1.18 - 1.41)\ \text{v}}$$

$$t = (2.86)\ (693\ \mu\text{sec.}) + 207\ \mu\text{sec.}$$

$$t = 2197\ \mu\text{sec.}$$

Using the maximum velocity of wave propagation of 4950 ft./sec., the depth of water which can be successfully measured is

$$\text{Maximum Depth Measurement (Extrapolated)} = (4950)\,(2197/2) = 5.4 \text{ ft.}$$

Two items concerning this discussion must be presented. First, the amplifier gain setting, as reported in Appendix A, was used. Variation of this adjustment will affect the maximum measurement depth. Second, the repeating echos of the bottom trace were not used for this maximum range determination because the repeating echo attenuation differed from the measured first echo attenuation which was observed from the upper and middle traces. To undertake a discussion of this signal attenuation difference or of propagation loss in general, is not the purpose of this section or of this paper. Rather, the purpose of expressing the ultrasonic considerations is to provide engineering data for the solution of a digital measurement problem.

The 0 - 2 ft. range measurement is illustrated by Figure 27. The oscilloscope traces, from top to bottom, present the outputs of amplifier #1, G. P. G. #1, amplifier #2, and G. P. G. #2. The manner in which Figures 26 and 27 were obtained is of some interest to future operators of the instrument. To obtain the repetitious operation which is illustrated by the figures, it was necessary to ground the output of NOR #1. By this action, the timing counter does not stop its counting at count 15 to wait for another start signal.

Projector Beam Angle

The sharp projector beam angle was mentioned by Massa[3] as a prerequisite for successful ultrasonic measurement. At the measurement frequency of the digital transducer, however, the very sharp beam angle of the commercial projectors was a disadvantage for two reasons. First, the original design of the sound projector arrangement could not be realized because of the sharp beam angle. Figure 28 illustrates this original design which utilized the second sound projector as only a receiver. The fixed distance for this arrangement was 0.512 ft.

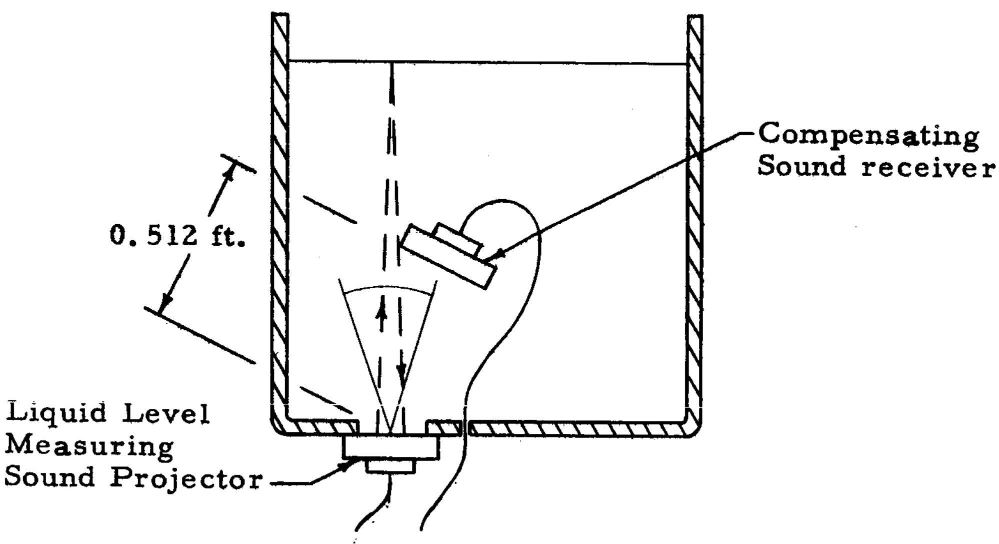


Figure 28. Original Ultrasonic Arrangement

This arrangement was unsatisfactory because in order to obtain a sufficient ultrasonic signal for the compensating receiver operation, it was necessary for the normal axis of this unit to be aligned with the normal axis of the sound projector. Thus the liquid level measurement signal was prevented from reaching the surface.

The second disadvantage created by the sharp beam angle was that of the critical alignment which was required between the normal of the sound projector and the surface. The solution was to provide the base of the sound projector assembly with an adjustable three point support. This can be seen in Figure 23.

The tank wall proximity to the path of the ultrasonic measurement signal had no effect on the signal or on the operation of the digital transducer. This was demonstrated by moving the sound projector assembly near a wall of the tank, by realigning the measuring transducer with the surface, and by observing the ultrasonic drive signals and the echos. It should be pointed out that design of the control logic for the reception of ultrasonic start and echo signals is such that a wide beam angle transducer could be used, since echos resulting from secondary radiation axes would return to the projector after the echo from the surface had produced correct operation of the counting control gates.

The specifications of the ultrasonic projectors are presented in Appendix C.

Logic Loading

Capacitive loading resulting from long wires was harmful to the operation of the high speed logic modules. In particular, the coupling of each output of Register #1 to an external buffer register by #22 gauge stranded wires six feet in length so loaded the high speed circuits that Register #1 would not count during the measurement operation. To overcome this problem and to provide logical read-out to another digital system, the f_c pulse input to Register #1 has been made available on Pin #13 of the connector on the front panel. In the upper left quadrant of Figure 15, this connector information is presented. By allowing an external 12 bit forward counter to receive these f_c pulses, which occur at a frequency of 20 kc./sec., the compensated liquid level measurement h will be available to an external digital system by reading the 10 highest order bits after the calculation operation has been completed.

CHAPTER V

THE PROBLEM IN DEPTH: CONCLUSIONS AND RECOMMENDATIONS

Depth Measurement Extension

The purpose of this section is to present observations about the digital transducer concept and its extension to greater depths. For illustration purposes, one may consider the measurement of a column of water 100 feet high to an accuracy of ±0.1% of the maximum range for a 40°F to 100°F temperature range. One discovers from Equation 6 the following facts:

1. The Δh_{min} is 0.1 ft. (1.2 inches),
2. The q_{max} is still 1000 quanta, and
3. The resultant quantization, K, is 10 quanta/ft.

By using an encoding accuracy factor of $k = 2$, Equation 25 states that measurement frequency f_m is 99 kc./sec. This measurement frequency is 50 times smaller than the present frequency of measurement and encoding of the Digital Liquid Level Transducer. In short, the digital quantization and temperature compensation of a liquid level measurement for the same measurement accuracy becomes a simpler task as the maximum depth to be measured increases!

A simpler task also is the development of the ultrasonic projectors, pulse generators, and amplifiers. For example, conventional ultrasonic depth measurement devices with analog read-out are commercially available at a cost of less than $150 for water ranges of 100 feet or more.[11]

Measurement Concept Conclusions

The validity of the measurement concept of the Digital Liquid Level Transducer can be discussed as follows:

1. The compensating time measurement does free the instrument from errors introduced by changes in the velocity of wave propagation. Since changes in velocity of wave propagation result from temperature and density changes, then changes in these items also have no effect on the compensated digital measurement.
2. The digital transducer is free from errors resulting from changes in the encoding and calculation frequencies. This capability implies that no frequency calibration is ever required.
3. The capacity for wide variations in the measurement frequency without adverse effect on the digital answer implies that the determination of f_m at the liquid temperature extreme which produces the highest velocity of sound propagation is not a strict requirement.
4. The necessity of maintaining a smooth water-air interface increases in importance as the wave length of the measurement frequency decreases.

5. The physical realization of the digital transducer instrument for a particular depth and accuracy is easier to attain as the maximum distance to be measured is increased.

Design Conclusions

Conclusions which involve the design and logical implementation of the Digital Liquid Level Transducer are presented as follows:

1. The system accuracy $+0.14\%$ to -0.06% of the full range when measuring from a smooth water-air interface indicates that the average accuracy of $\pm 0.1\%$ of the full range has been attained. Further, this accuracy result illustrates that the selection of an encoding accuracy factor of $k = 2$ is satisfactory.
2. The concept of constructing an entire digital sub-system on a single printed circuit card reduced the long wire loading problems and simplified the interconnections between the logic modules. The time required for the printed circuit layout is the price to be paid for using the concept.
3. The lack of synchronization between the measurement frequency, f_m, and the ultrasonic start signal did not adversely affect the compensated digital result.
4. The utilization of the gated timing method greatly simplified the check-out of the digital sub-systems.

5. The dual utilization of Register #1 in the measurement and calculation operations is undesirable because of the capacitive loading created by the long wire outputs.

Recommendations for Future Activity

The recommendations for the further development of the Digital Liquid Level Transducer are as follows:

1. The addition of another 12 bit, low speed, forward counting register would eliminate the troublesome dual utilization of Register #1. To do this requires the designing of a new Register #1 on one circuit card which would be placed in the available space between modules #13 and #14. The present Register #1 locations would be used for the additional forward counting register with its serial shift logic.
2. By making a higher d. c. voltage source available to the digital transducer, the ultrasonic pulse generators could be redesigned to produce larger ultrasonic drive signals. Thus the present maximum range limitation would be raised.

APPENDIX A

CIRCUIT MODULES

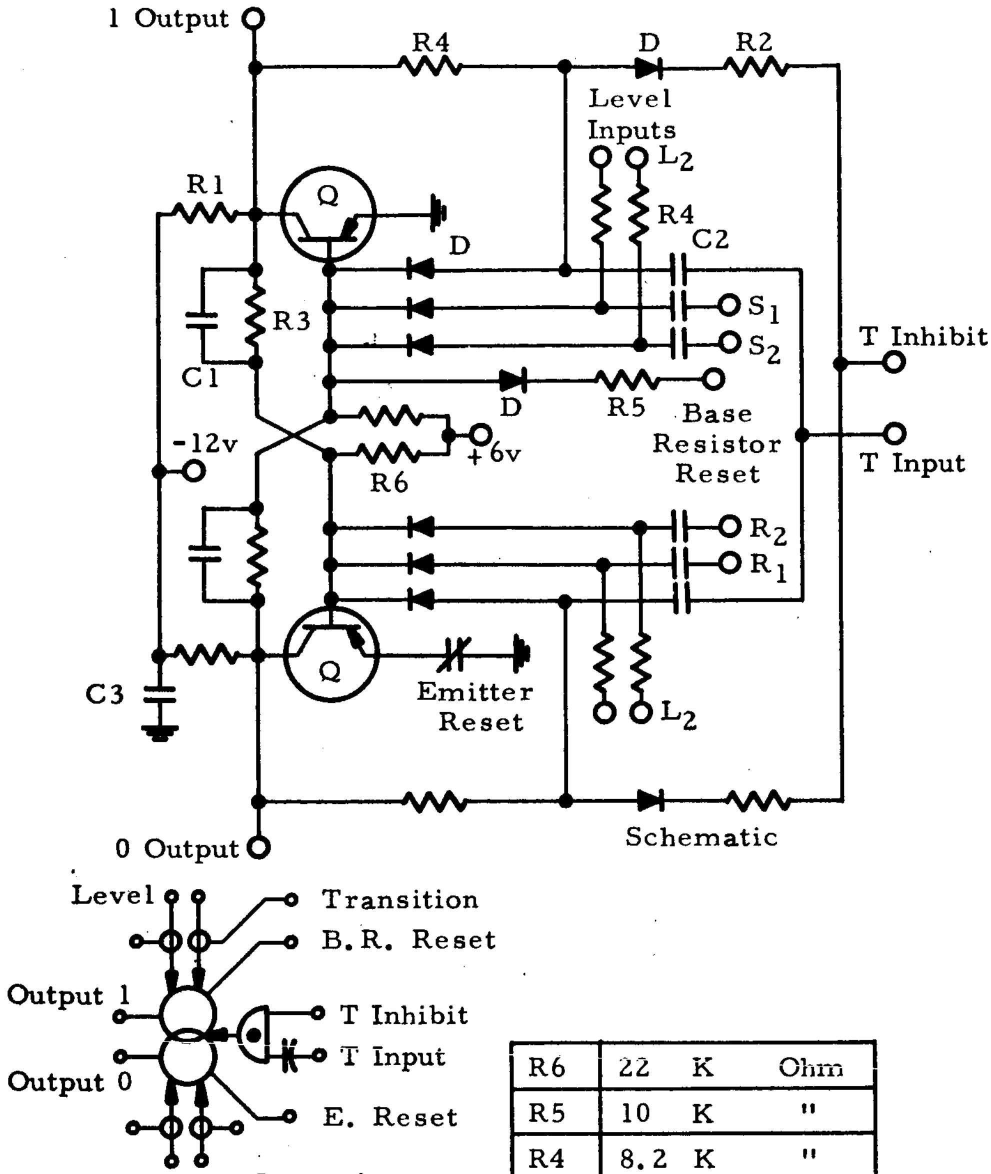
The circuit modules of the Digital Liquid Level Transducer are both digital and analog. The function of this appendix is to describe the operation of each module and to present its circuit schematic and logical symbol.

Digital Devices

Flip-flop

The flip-flop or bistable multivibrator is a two stable state memory device. Figures 29 (a & b) present three flip-flops which differ, not in basic operation, but rather in how fast they will switch between stable states. The two stable states are represented by 0 volts and a negative potential (-12 volts for the 100 kc. device and -6 volts for the 1 and 5 Mc. devices). The frequency of the signal on the T input which each flip-flop can successfully follow is indicated by its name.

Information is stored in the flip-flop by placing a positive going voltage transition on the T input or on one of the other transition inputs: S_1, S_2, R_1 and R_2. The T Inhibit input and the level inputs function as control gates which enable or inhibit the transition from causing the flip-flop to change state. If the level input is at 0 volts, then the transition will cause state change. The transition will be

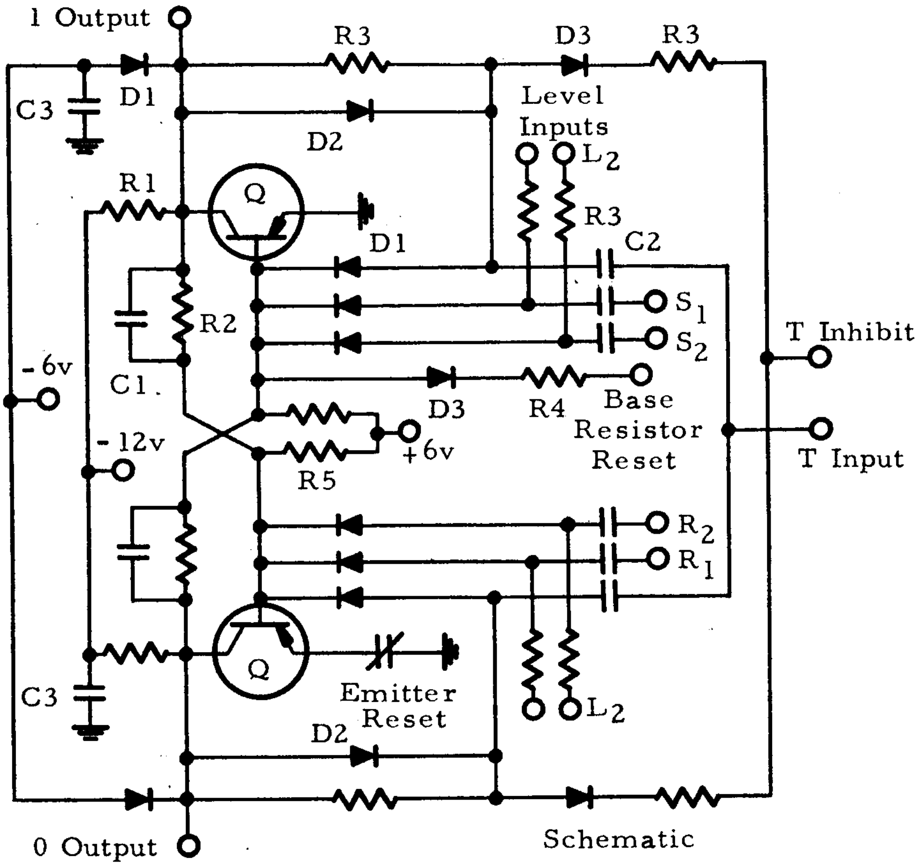


All resistors 1/4 w, ± 10%

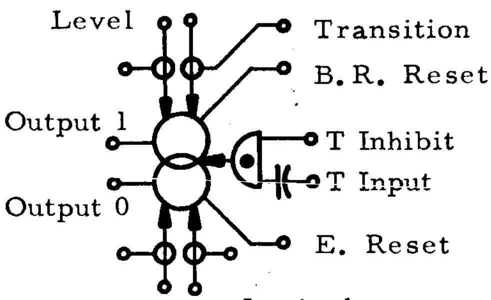
R6	22 K	Ohm
R5	10 K	"
R4	8.2 K	"
R3	6.8 K	"
R2	3.3 K	"
R1	1.0 K	"
D	1N456	
Q	2N404	

C3	0.05	μf
C2	390	pf
C1	82	pf

Figure 29 (a). Flip-flop, 100 kc./sec.



Schematic



Logical Symbol

For 1 Mc. design: Diodes D2 are removed.

R5	47 K	Ohm
R4	10 K	"
R3	8.2 K	"
R2	6.8 K	"
R1	1.0 K	"
D3	1N456	
D2	FD829	
D1	FD829	
Q	2N711B	

All resistors 1/4 w, ± 10%

C3	0.05	μf
C2	20	pf
C1	10	pf

Figure 29 (b). Flip-flop, 1 Mc./sec. and 5 Mc./sec.

inhibited if the level input is at a negative voltage.

The following definition of flip-flop operation will aid in the explanation.

1. When the 1 Output of the flip-flop is at 0 volts, the device is said to be in the reset condition.
2. When the 1 Output of the flip-flop is at the negative potential stable state, the device is said to be in the set condition.

With these definitions the operation of the Emitter Reset and the Base Resistor Reset can be presented. By manually opening the normally closed Emitter Reset switch, the flip-flop is reset, since the 1 Output becomes ground. Also the flip-flop becomes reset by logically applying a negative potential to the Base Resistor Reset. Thus a manual and a logical method are available for putting the flip-flop in the reset condition. An Emitter Set and a Base Resistor Set can be created by placing the circuit configurations which are involved on the corresponding terminals of the opposite transistors.

Three types of transition signals can result in a state change. These are the trigger, the set, and the reset signals. The positive going transition applied to the T input results in a state change of the flip-flop. The application of a second transition results in the flip-flop's returning to the original state.

The set and reset actions result when the two resistor control levels L_2 of R_2 and S_2 are coupled to 0 Output and the 1 Output terminals, respectively. A transition set signal applied to the S_2 terminal causes the flip-flop to enter or to be maintained in the set condition. A transition reset signal applied to the R_2 terminal causes the flip-flop to enter or to be maintained in the reset condition.

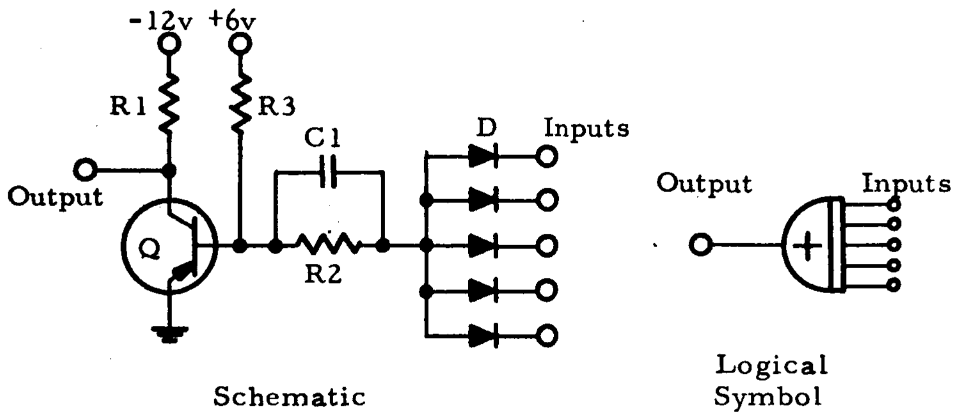
NOR Gate

The NOR Gate is a multi-input, one output logic element which can be used to synthesize logical AND, OR, and NOT functions. Figure 30 (a) illustrates a NOR Gate with five inputs. For a NOR 1, all of the diodes are removed.

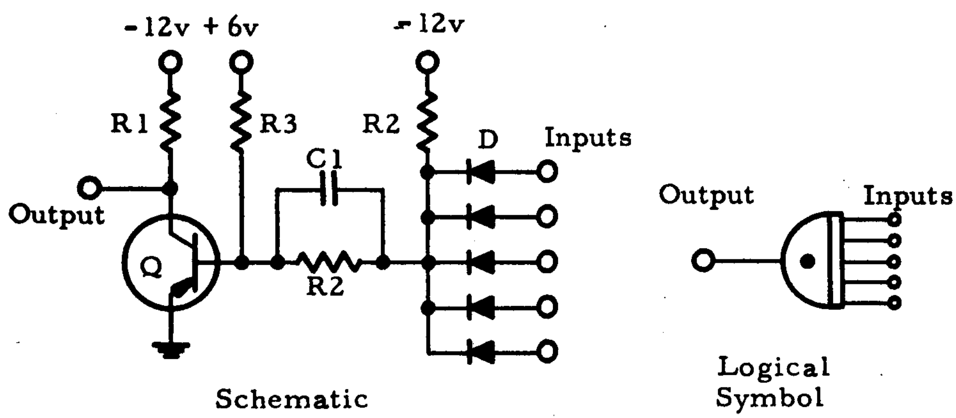
The synthesis of the AND, OR, and NOR functions is possible by introducing a new set of definitions which relates the signal polarities to logic values.[12] Figure 31 illustrates the formation of the three functions. The AND function, $f = A\bar{B}C$, is generated when all of the inputs are simultaneously at the +(0 volts) potential. To emphasize the formation of the AND function, the dot is added to the NOR 3 symbol; and the voltages present on the inputs and output are shown.

The OR function is generated when any one or all of the inputs are at the negative potential. The plus sign which is added to the NOR 3 symbol and the input and output voltages illustrate the formation of the OR function.

The NOT and the Identity functions are similar. The NOT function is used to obtain a logical inversion, while the Identity function is used to obtain a signal inversion. The Identity function



(a) NOR 5 Logical Gate



(b) NAND 5 Logical Gate

All resistors 1/4 w, ± 10%

C1	82		pf	R1	1.0 K	Ohm
R3	22	K	Ohm	D	1N456	
R2	6.8	K	"	Q	2N404	

Figure 30. Logical Gates:
NOR and NAND, 100 kc./sec.

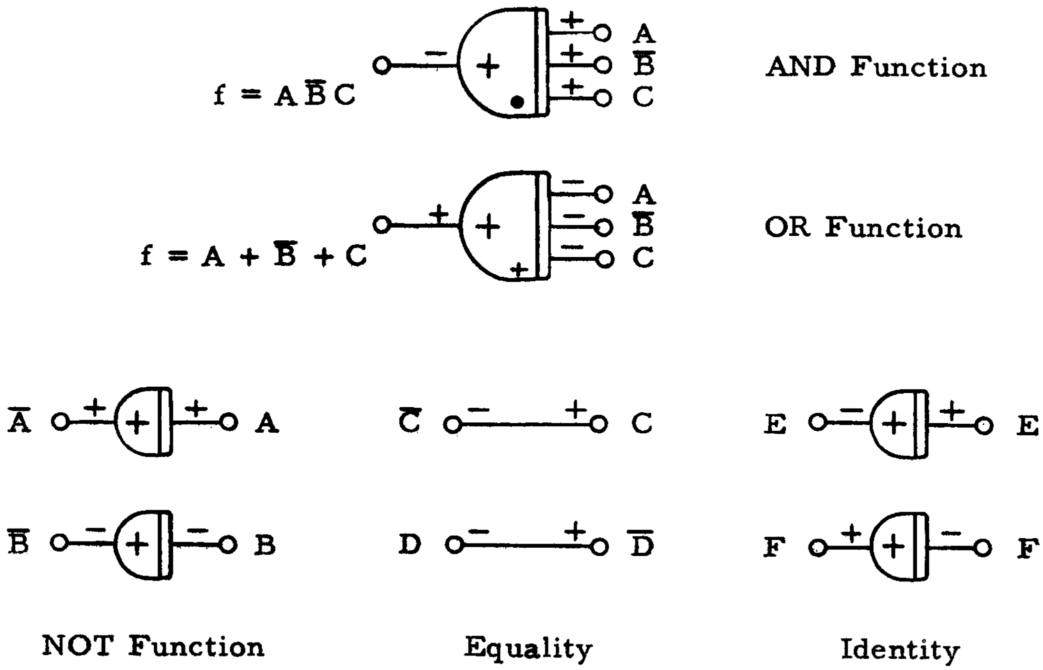


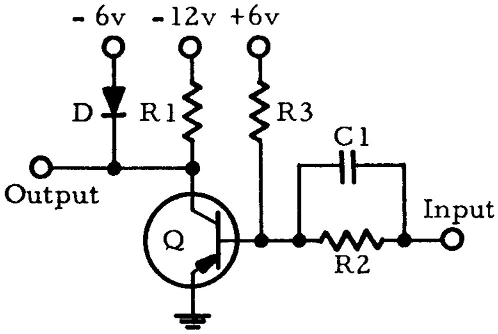
Figure 31. AND, OR, and NOT Functions from the NOR

produces the opposite polarity for the same logical function. The Equality function implies both logical and polarity inversion.

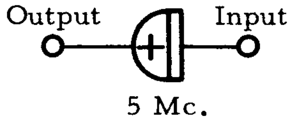
Figure 32 presents the high speed versions of the NOR 1 and NOR 2. The synthesis technique just described applies equally well.

NAND Gate

Figure 30 (b) presents the configuration of the multi-input, one output NAND Gate which can be used to generate AND and OR functions. The existence of this device can be justified by noting that the generated AND function has a +(0 volt) output. The NOR Gate which generated the AND function was true at the negative potential. The OR function which is generated by the NAND element

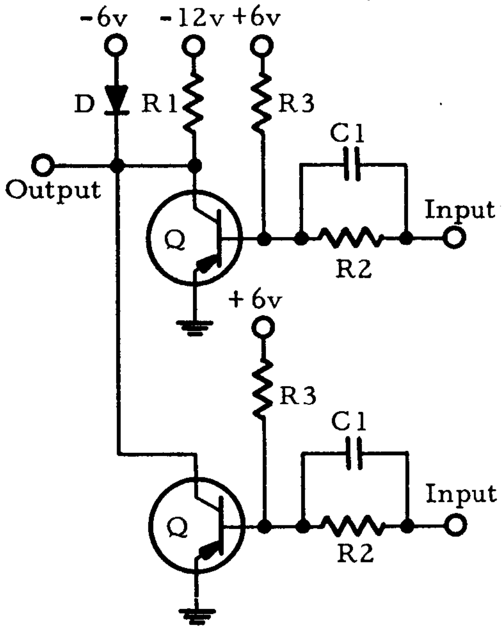


Schematic

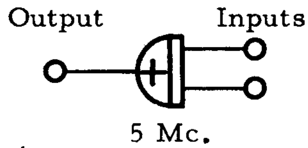


Logical Symbol

(a) NOR 1



Schematic



Logical Symbol

(b) NOR 2

All resistors 1/4 w, ± 10%

C1	10 pf	R1	1.0 K Ohm
R3	27 K Ohm	D	FD 829
R2	6.8 K "	Q	2N711B

Figure 32. NOR Gates, 5 Mc./sec.

is true when the output is at the negative potential. Thus the NAND Gate has value when an AND function at the +voltage level or an OR function at the negative potential is desired. Figure 33 illustrates the NAND circuit performing the AND and OR logical functions.

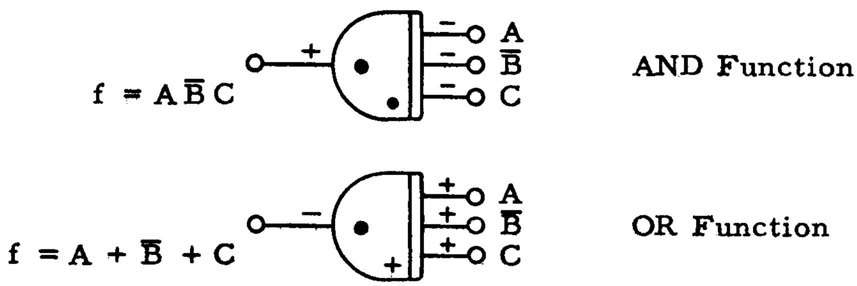


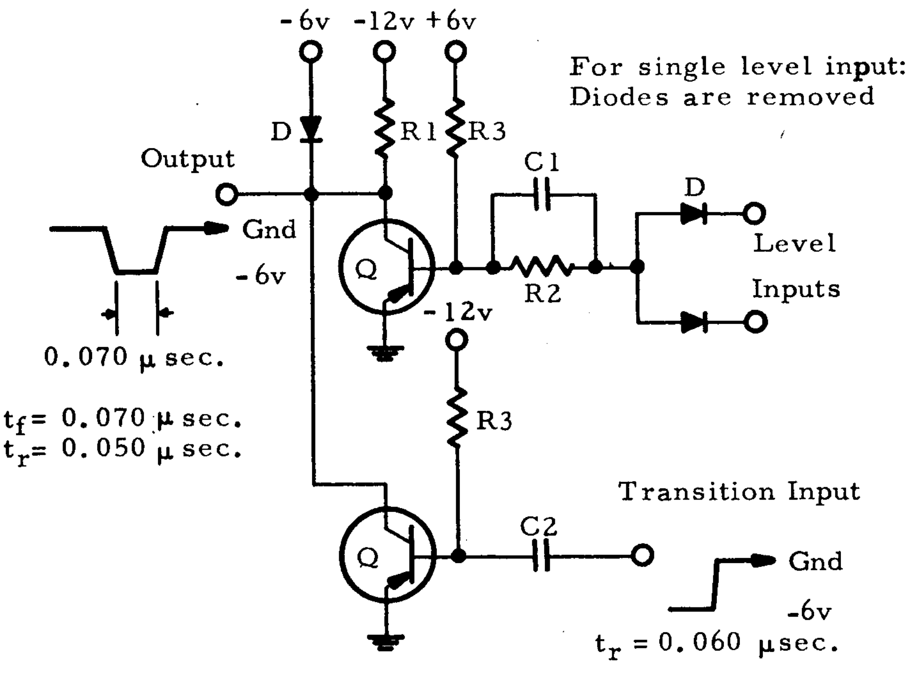
Figure 33. AND and OR Functions from the NAND

Pulse Generator

The pulse generator is a pulse output, transition input, digital device. If the transition voltage input always produces an output, then the device is a pulse generator. If the pulse output is controlled by an additional voltage level or levels, then the device is a gated pulse generator. Figures 34, 35, and 36 present the pulse generators and gated pulse generators and their logical symbols. For all of the gated devices, a pulse output is achieved only if the voltage levels on all level inputs are simultaneously 0 volts.

Nine Input Gated Pulse Generator

The function of the nine input gated pulse generator is to en-



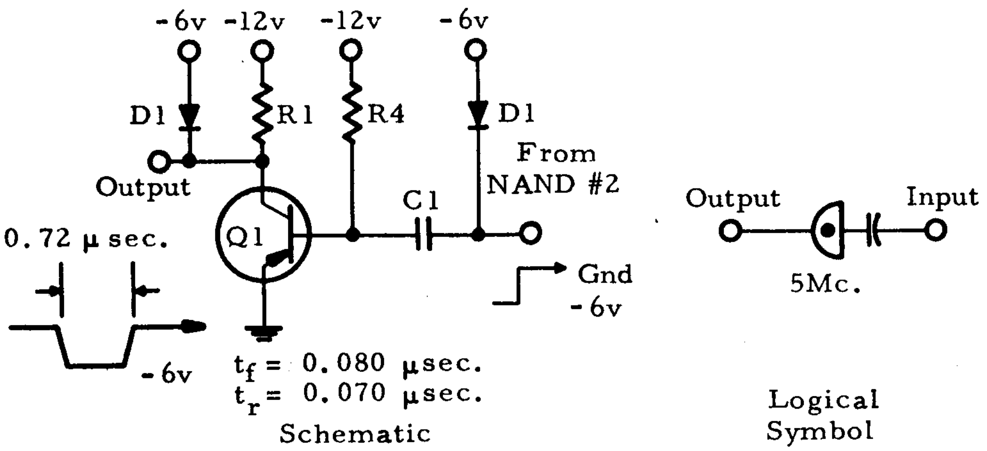
Schematic

Logical Symbols

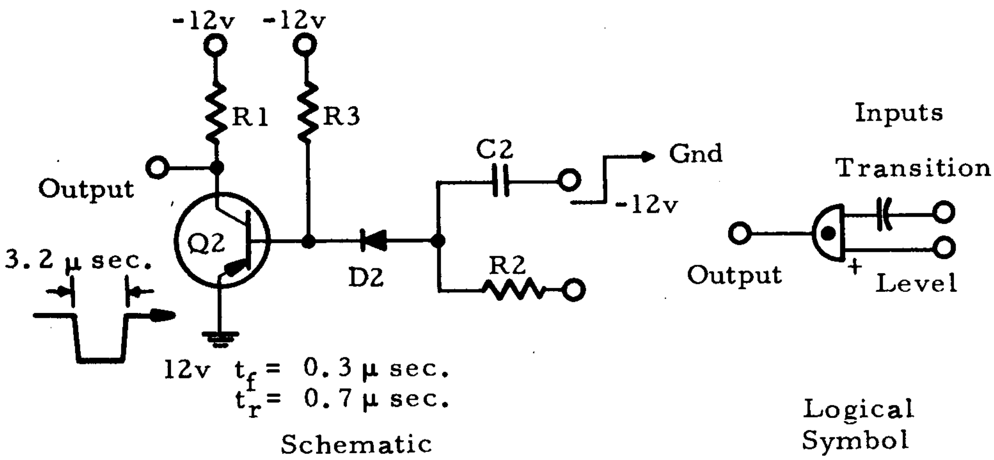
All resistors 1/4 w, ± 10%

		R2	3.3 K Ohm
C2	20 pf	R1	1.0 K "
C1	10 pf	D	FD 829
R3	22 K Ohm	Q	2N711B

Figure 34. Gated Pulse Generators, 5 Mc./sec.



(a) Pulse Generator #3

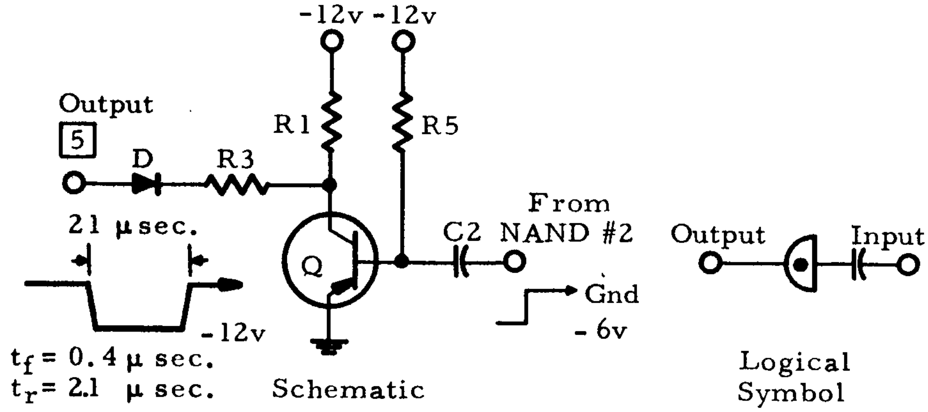


(b) Gated Pulse Generator #5

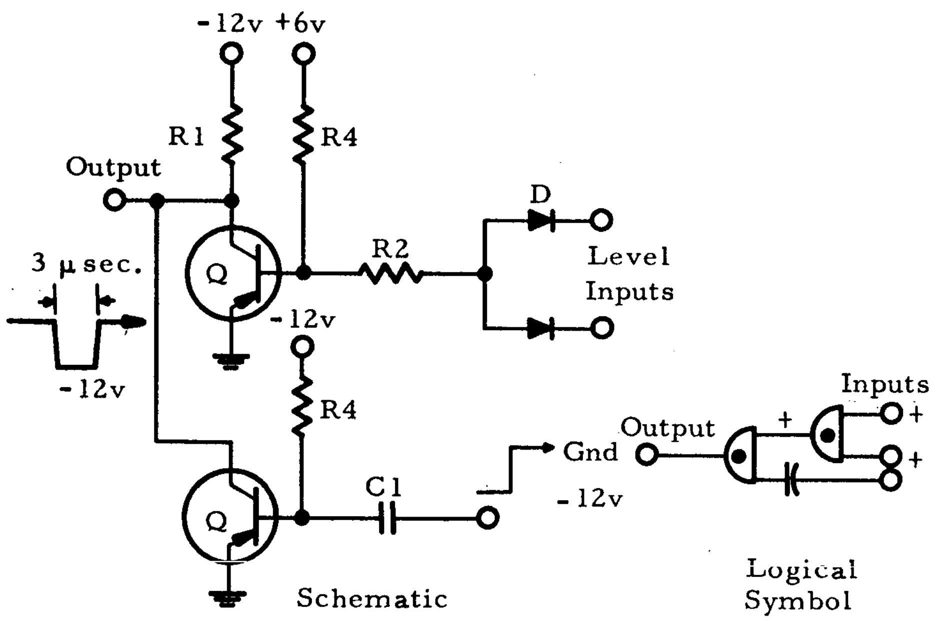
All resistors 1/4 w, ± 10%

C2	470 pf	R1	1.0 K Ohm
C1	30 pf	D2	1N456
R4	47 K Ohm	D1	FD829
R3	22 K "	Q2	2N404
R2	8.2 K "	Q1	2N711B

Figure 35. Pulse Generators #3 and #5



(a) Pulse Generator # 6



(b) Gated Pulse Generator #7

All resistors 1/4 w, ± 10%

		R3	8.2 K Ohm
C2	0.001 μf	R2	6.8 K "
C1	390 pf	R1	1.0 K "
R5	47 K Ohm	D	1N456
R4	22 K "	Q	2N404

Figure 36. Pulse Generators #6 and #7

able the summing of nine transition inputs. Figure 37 presents the schematic and the logical symbol. For each transition input, there is a corresponding level input which enables or inhibits the passage of the transition by the application of a +(0 potential) or -(negative potential) voltage, respectively.

Free Running Multivibrator

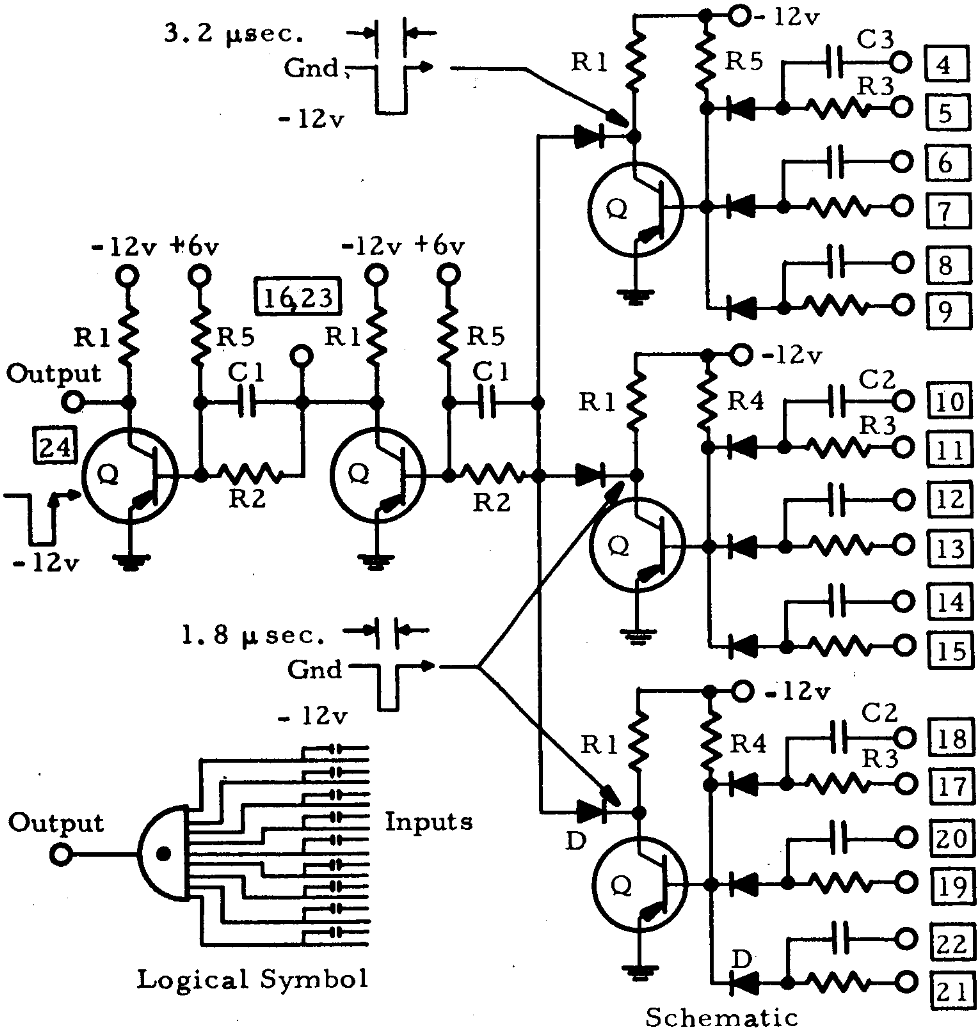
The free running multivibrator is a digital device which possesses no stable state. It functions as the master clock for the operation of the other digital logic modules. Figure 38 presents the FRMV. The frequency and asymmetry of the output signal are achieved by adjusting the components, R_3, R_6, C_4, and C_5.

Crystal Oscillator

The crystal oscillator is another digital device which possesses no stable state. The function of this device is to provide the measurement frequency, f_m for the encoding of times t_1 and t_2. The frequency of operation is determined by the selection of a plug-in crystal. Figures 39 and 44 present the schematic and output signal of the crystal oscillator.

Schmitt Trigger

The Schmitt Trigger logic module functions as the interface between the analog and digital signals in the transducer. Figure 40 presents the device, its logical symbol, and its input and output

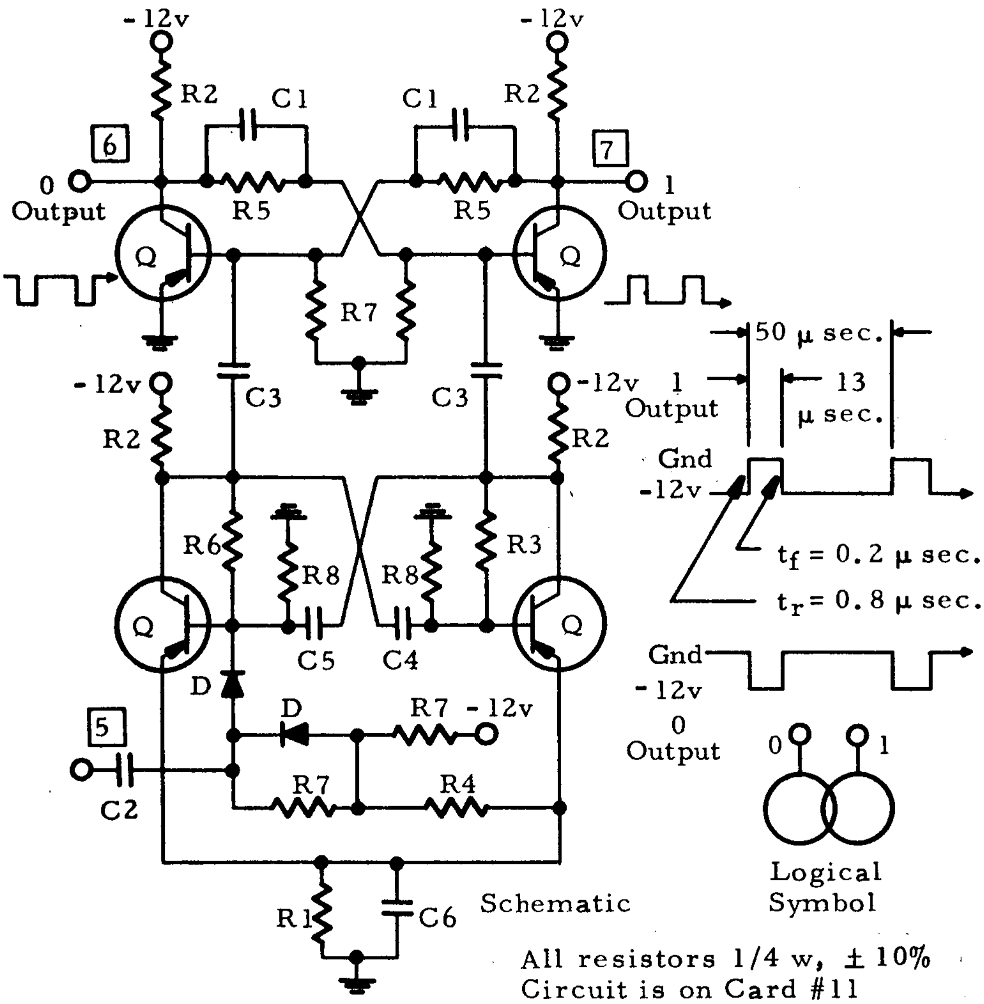


All resistors 1/4 w, ± 10%

Circuit is Card #2

C3	390		pf	R3	8.2	K	Ohm
C2	270		pf	R2	6.8	K	"
C1	82		pf	R1	1.0	K	"
R5	22	K	Ohm	D	1N456		
R4	15	K	"	Q	2N404		

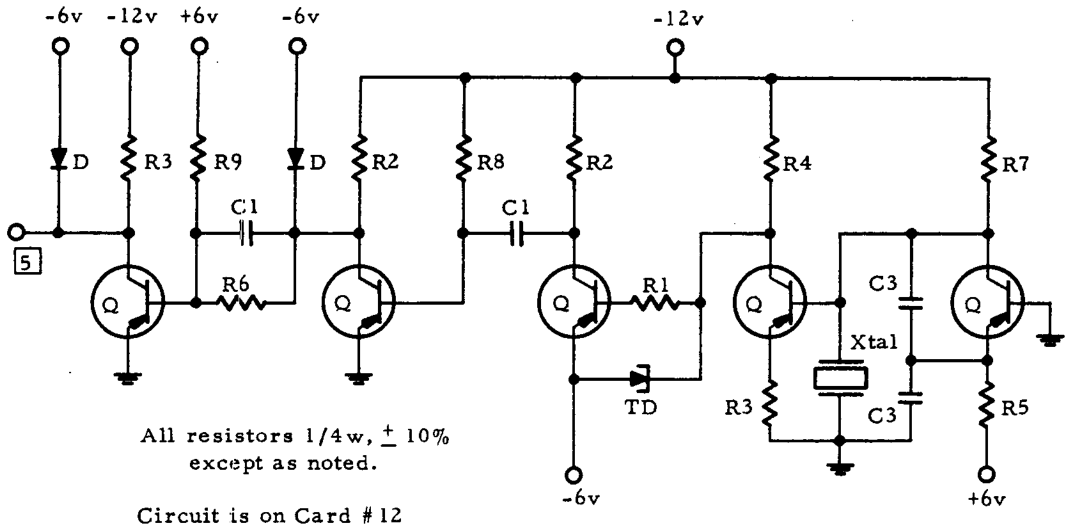
Figure 37. Nine Input Gated Pulse Generator



All resistors 1/4 w, ± 10%
Circuit is on Card #11

C6	0.01	μf	R6	18	K	Ohm
C5	0.0047	μf	R5	6.8	K	"
C4	0.0039	μf	R4	4.7	K	"
C3	390	pf	R3	3.3	K	"
C2	220	pf	R2	1.0	K	"
C1	82	pf	R1	330		"
R8	180	K Ohm	D	1N456		
R7	22	K "	Q	2N404		

Figure 38. Free Running Multivibrator

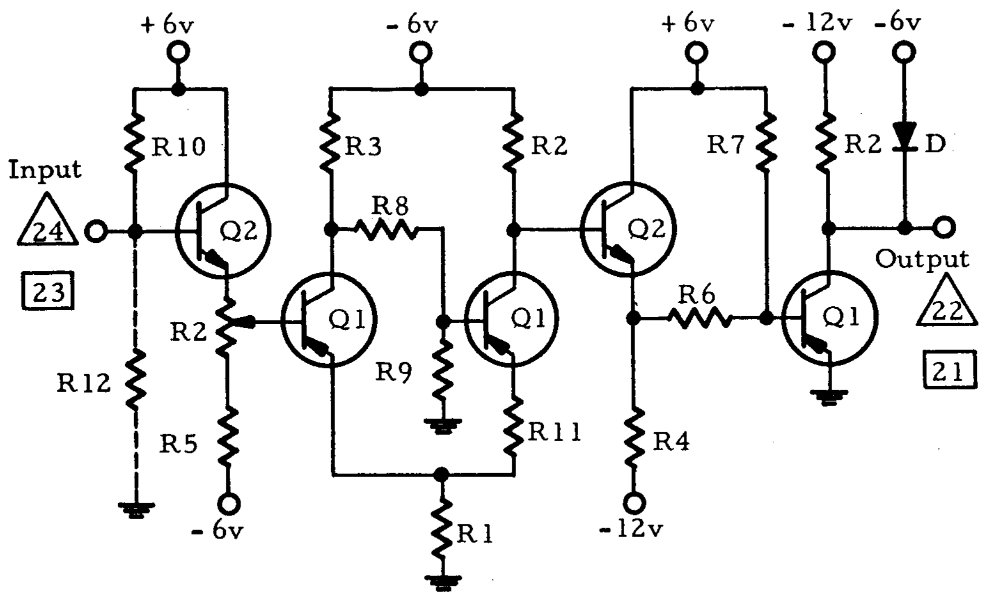


All resistors 1/4w, ± 10%
except as noted.

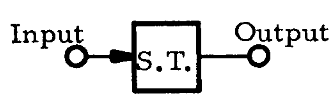
Circuit is on Card #12

Xtal	4.95 Mc./sec, ± 0.01%	R5	6.2 K Ohm, ± 5%
C3	220 pf, (TCC-T22 NPO)	R4	1.5 K "
C2	33 pf	R3	1.0 K "
C1	10 pf	R2	680 "
R9	27 K Ohm	R1	150 "
R8	15 K "	D	FD829
R7	8.2 K "	TD	1N3714 (TD-2)
R6	6.8 K "	Q	2N711B

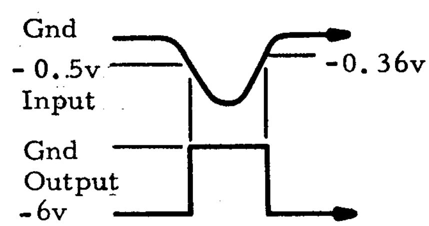
FIGURE 39. CRYSTAL OSCILLATOR



Schematic



Logical Symbol



t_r = 0.060 μ sec.
t_f = 0.060 μ sec.

All resistors 1/4 w, ± 10%, except as noted.
For Q1 transistors with non-matched h_{fe}, R11 is experimentally determined.
R12 is on the amplifier output.
Circuits are on Card #13.

		R5	4.7 K Ohm
R12	See note	R4	2.2 K "
R11	See note	R3	1.2 K "
R10	470 K Ohm	R2	1.0 K "
R9	33 K "	R1	220 Ohm, ±2%
R8	12 K "	D	FD829
R7	10 K "	Q2	2N2712
R6	5.6 K "	Q1	2N711B

Figure 40. Schmitt Trigger, 5 Mc./sec.

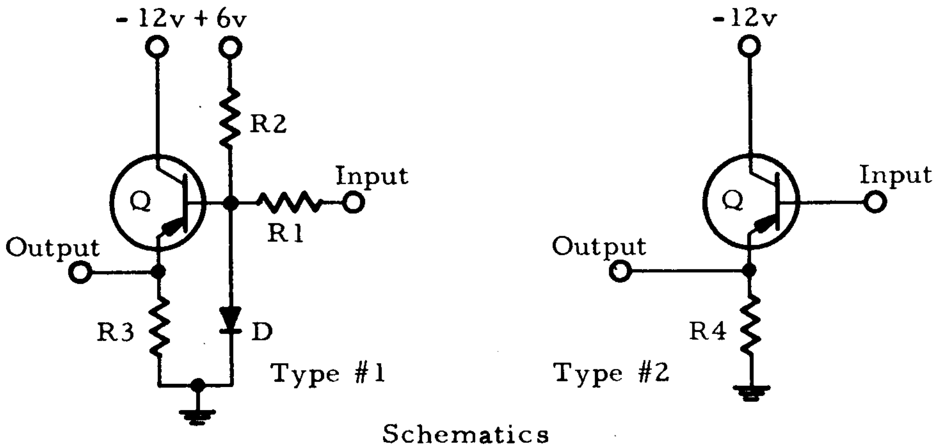
signal shapes. The input which is sensitive only to voltage level has no effect on the -6 volt output until a -0.5 volts is sensed. At that time the trigger circuit upsets, and the output voltage makes a positive going transition to 0 volts. Later in time, when the input voltage becomes less negative than -0.36 volts, the output returns to its -6 volt level. The potentiometer, R_2, enables circuit adjustment to achieve the -0.5 volt upset level. Fixed resistors R_2 and R_3 insure stability of the circuit by providing the 0.14 volt hysteresis between the upset and recovery voltages.

Emitter Follower

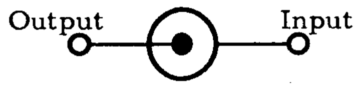
The operation of the emitter follower is characterized by its name. The voltage on the output follows that on the input. Through its use the simultaneous logical setting and resetting of a large number of flip-flops can be achieved by using the Base Resistor Set or Reset terminal of each flip-flop. Figure 41 (a) presents two types of emitter followers. Type #1 is utilized when the input signal may be interrupted. For applications in which the emitter follower input is permanently attached to a digital source, type #2 can be used.

Light Driver

The light driver circuit which is used in the transducer is presented in Figure 41 (b). For illustration purposes, the indicator light has been shown on the schematic. A negative voltage signal on the input will cause the light to turn on.



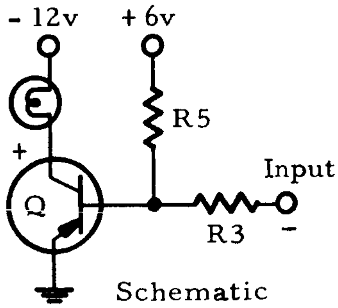
Schematics



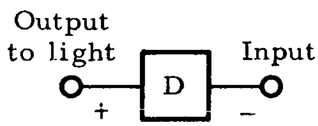
Logical Symbol

(a) Emitter Follower

Lights:
Dialco #39-28-
1433 (Amber)
1431 (Red)



Schematic



Logical Symbol

(b) Light Driver

All resistors 1/4 w, ± 10%

			R2	6.8 K	Ohm
R5	47 K	Ohm	R1	680	"
R4	22 K	"	D	1N456	
R3	10 K	"	Q	2N404	

Figure 41. Emitter Follower and Light Driver

Analog Devices

The analog modules of the digital transducer are those which drive the sound projectors and which amplify the returning echos.

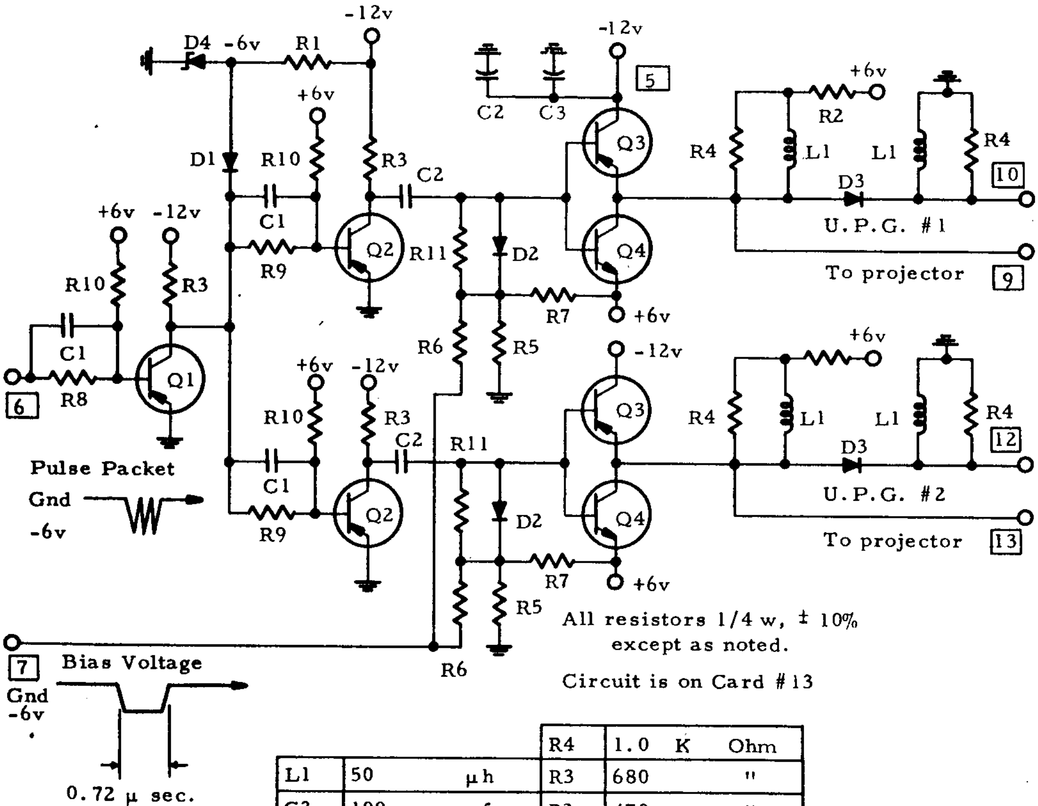
Ultrasonic Pulse Generator

The function of the ultrasonic pulse generator is to provide the sound projector with a packet of pulses of the frequency f_m and to couple the returning echo, which is received by the sound projector, to the amplifier. Figure 42 presents the schematic of both ultrasonic pulse generators, #1 and #2.

The operation of each generator can be described by observing the sending and receiving of an ultrasonic signal. During sending, the pulse packet and the bias voltage are applied to their respective inputs. Transistor pairs Q_3 and Q_4, which form complementary emitter follower circuits, drive the sound projectors which are coupled to terminals #9 and #13. The purpose of the bias voltage is to insure that the sound projectors receive the full voltage swings of the pulse packet. This is accomplished by back biasing the amplifier coupling diodes D_3. For echo receiving, diodes D_3 are forward biased, since the bias voltage is not present. Now a voltage pulse created by the echo will be coupled through the forward biased coupling diode into the respective amplifier.

Amplifier

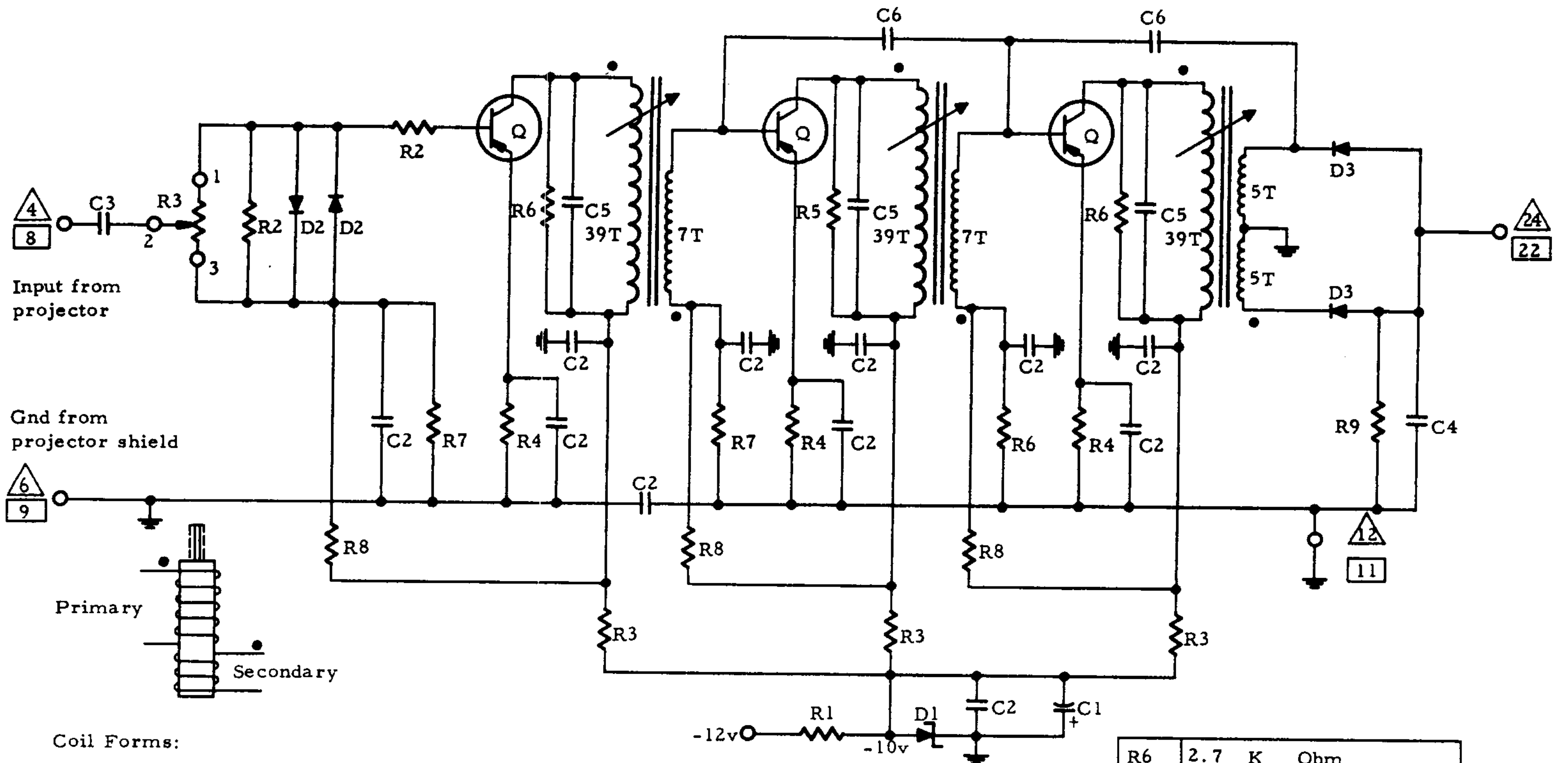
The amplification of the echo voltage pulse to a voltage poten-



			R4	1.0 K	Ohm
L1	50	µh	R3	680	"
C3	100	µf	R2	470	"
C2	0.05	µf	R1	100 Ohm, 1/2 w	
C1	10	pf	D4	1N3828A	
R11	47 K	Ohm	D3	1N456	
R10	27 K	"	D2	1N60	
R9	10 K	"	D1	FD829	
R8	6.8 K	"	Q4	TI411	
R7	4.7 K	"	Q3	2N2906	
R6	2.7 K	"	Q2	2N3323	
R5	2.2 K	"	Q1	2N711B	

FIGURE 42. ULTRASONIC PULSE GENERATOR

tial which will successfully operate the digital circuitry is accomplished in the three stage amplifier of Figure 43. The transformer coupled, tuned stages produce an amplifier system with a frequency band pass of approximately 1 Mc. and with a center frequency of 4.9 Mc. The amplifier power gain is 26 db, and the frequency band pass is illustrated in Figure 45. The 4.00 Mc./sec. frequency marker is located 1.5 cm. to the left of center. The 5.00 Mc./sec. marker is at the center of the illustration. Because of the diode rectification on the output of the final stage, the characteristic amplifier curve is inverted.



Coil Forms:

Cambion PLS5, Core No. 20063 - B

Primary: 34 enamel wire, close-wound.

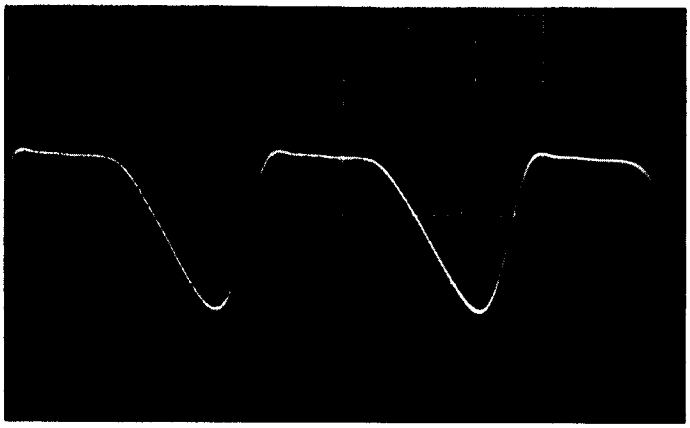
Secondary: 28 enamel wire, close-wound over primary winding.

All resistors 1/4 w, ± 10% except as noted.

Circuit is Card #14

		R6	2.7 K Ohm
C6	5 pf	R5	2.2 K "
C5	39 pf	R4	1.0 K "
C4	390 pf	R3	100 "
C3	0.01 μf	R2	47 "
C2	0.05 μf	R1	27 " , 1/2 w
C1	25 μf	D3	1N60
R9	47 K Ohm	D2	FD829
R8	10 K "	D1	1N3020A
R7	4.7 K "	Q	2N3323

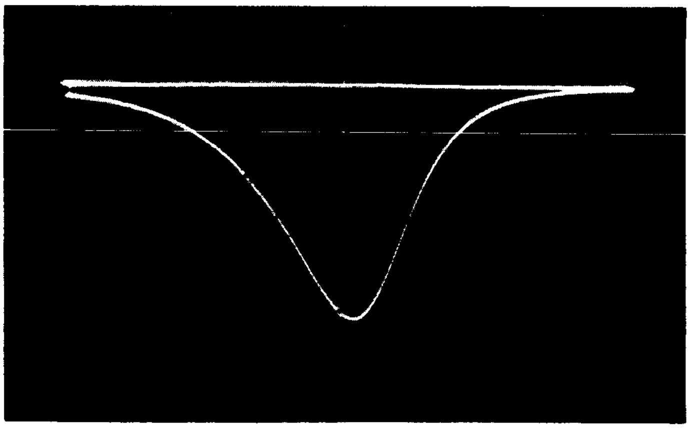
FIGURE 43. AMPLIFIER, 4.9 Mc./SEC.



Horizontal:
0.050 μ sec. /cm.

Vertical:
2 volts/cm.

Figure 44. Oscillator Output



Horizontal:
See text

Vertical:
0.2 volts/cm.

Figure 45. Amplifier Frequency Band Pass

APPENDIX B

BINARY FORWARD AND BACKWARD COUNTING

The purpose of this appendix is to present the logical implementation of forward and backward counting counters which operate on positive going voltage transitions. The binary count sequences for a 3 bit counter are presented in Table 7.

Forward Count Sequence Decimal	Forward Count Sequence Binary	Backward Count Sequence Decimal	Backward Count Sequence Binary
	$2^2 2^1 2^0$		$2^2 2^1 2^0$
	A B C		D E F
0	0 0 0	0	0 0 0
1	0 $\boxed{0}$ 1	7	1 1 1
2	0 $\boxed{1}$ 0	6	1 $\boxed{1}$ 0
3	0 1 1	5	1 $\boxed{0}$ 1
4	1 0 0	4	1 0 0
5	1 0 1	3	0 1 1
6	1 1 0	2	0 1 0
7	1 1 1	1	0 0 1
0	0 0 0	0	0 0 0

Table 7. Binary Count Sequences

For forward counting, the following is observed from the binary count sequence:

When a lower order bit goes from the set to the reset state, the next higher bit changes state.

Thus when binary bit C goes from set to reset for the count of 1 to 2, binary bit B changes state. It was reset at count 1 and is set at count 2. For the count change of 7 to 0, as bit C goes from the set to the reset condition, bit B changes from the set to the reset condition; and A changes from the set to the reset condition.

By employing one of the flip-flop types of Appendix A, a forward counter can be formed by connecting the 1 Output of each flip-flop to the Trigger input of the next higher order flip-flop.

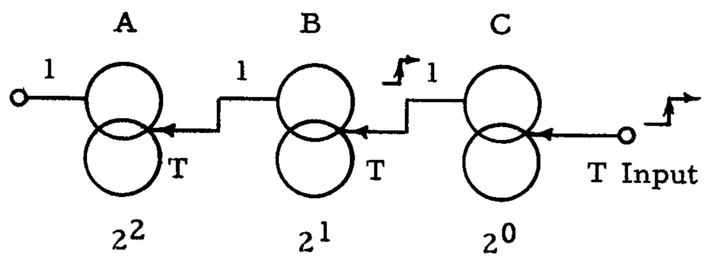


Figure 46. Binary Forward Counter

Each time flip-flop C goes from the set to the reset condition, a positive going voltage transition occurs at its 1 Output. This transition causes flip-flop B to change state. Further application of positive going voltage transitions to the T input of C will cause the three flip-flops to count forward from 0 to 7.

For backward counting, the following is observed from the binary count sequence:

When a lower order bit goes from the reset to the set state, the next higher bit changes state.

By connecting the 0 Output of each flip-flop to the Trigger input of the next higher order flip-flop, a backward counter can be formed as Figure 47 illustrates.

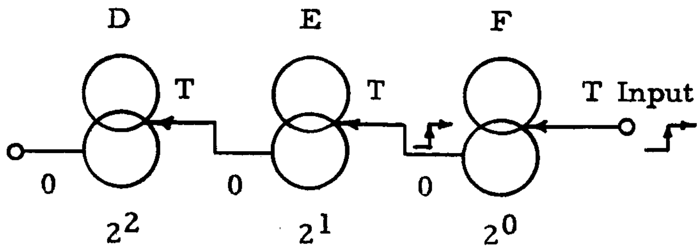


Figure 47. Binary Backward Counter

To show this is possible, one can consider that the count goes from 0 to 7. A positive going transition applied to F causes that flip-flop to go from the reset to the set condition. The positive going transition which is produced at the 0 Output will cause flip-flop E to go from reset to set. Finally, the transition from E will cause D to change to the set state also. Thus the backward counter counts from 000 to 111. Further transitions applied to the T input of F will result in the complete backward count sequence.

APPENDIX C

ULTRASONIC PROJECTOR SPECIFICATION

This section presents the projector specifications furnished by the manufacturer.

Projector Specifications

Ceramic crystal:	Barium titanate Ceramelec 1006 mix
Thickness frequency:	4.855 Mc./sec.
Radial frequency:	113.75 kc./sec.
Capacitance at thickness frequency:	0.0068 μf
Resistance at thickness frequency:	32 Ohms
Physical dimensions (crystal)	
Thickness:	0.020 to 0.022 inches
Diameter:	0.84 inches
Physical dimensions (aluminum housing)	
Height:	0.75 inches
Diameter:	1.25 inches
Cable (15 feet):	RG58A/U
Cost:	$25/Projector
Manufacturer:	Erie Technological Products, Technical Materials Division, State College, Pennsylvania.

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