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DEVELOPMENT OF NONDESTRUCTIVE, AUTOMATIC TECHNIQUE FOR MONITORING AND RECORDING OF FATIGUE CRACK GROWTH

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SUMMARY

This summary will include the highlights of the previous two quarterly reports, FHR-3294 and FHR-3294-1.

This program has demonstrated the feasibility of a single tracking probe system to ultrasonically detect a crack or a slot. This system utilizes a surface wave and a manufactured reference signal. When machining the slots, incremental cuts, as small as 0.001-inch could be detected and automatically tracked by the comparison of two reflected signals.

The reflection technique is used to detect the leading edge of the crack. A single ultrasonic beam (Rayleigh wave) is transmitted on the surface of the material. The beam is positioned so that a portion of the signal is reflected from the crack, and a portion is reflected from a plate clamped across the specimen to produce a reference signal. The difference in amplitude between these two signals produces an error voltage that drives a servo-motor to position the transducer and maintain a balanced signal.

Many of the variables, such as specimen surface conditions change during fatigue cycling. Changes resulting from stress levels and minor changes in coupling are minimal because in most cases both signals are similarly attenuated. Signal attenuation does not affect the error voltage; hence, only fatigue crack propogation is monitored.

Investigations of the single tracking probe system have shown that it is operationally feasible to track the leading edge of the crack, to plot the angle of the crack, and to actually record an X and Y position of the crack. Knowledge of the crack-angle permits the insertion of a correction factor that enables the precise location of the crack leading edge.

In this study the surface wave was produced by an angled transducer. Two systems of coupling were evaluated; one system was oil coupled through a plexiglass block and the second system was an angled transducer, water coupled with a plexiglass block water container.

The water coupled system was found to produce the best results because it had less attenuation, the transducer remaines cool for the elevated temperature tests, and the coupling was much more uniform and produced the least friction thus requiring a minimum of torque.

Dynamic fatigue testing data indicates that a crack can be detected with the ultrasonic technique before it can be seen through a transit.

One of the most important aspects of the two signal techniques for monitoring of cracks is the repeatability of the system with an error ± 0.005-inch. This can be accomplished if all items are set up and tuned the same, i.e., considering the indicated transducer location errors that are initially introduced, and starting with a round hole and changing to a slot configuration, will give duplicated results within ± 0.005-inch.

Without an automatic gain control system it is important that the system be adjusted to have the maximum amplitudes of the crack and the reference signal approximately equal. This reduces the error tolerance when there are amplitude changes in the balanced signal.

In this study Republic developed an electronic system to process the two reflected signals. These signals, when integrated, serve to produce an error voltage signal to drive a servo motor. A dual-gated system was designed to select only the signal areas required and to eliminate all unwanted signals and noise. A selective time (0 to 115 μsec) delay line is used to delay the crack signal to bring it in phase with the reference signal. The two signals are then amplified and one signal made negative. The signals are compared; and the signal with greater amplitude is used to determine the error voltage polarity. This signal is injected into the servo amplifier that in turn controls the servo motor speed and direction.

Additional research is necessary to miniaturize the transducer assembly. This will reduce the overall weight of the system and the resultant eccentric loading on the fatigue specimen. To make the system foolproof, electronically, and to produce a direct reading monitoring technique, an automatic gain control should be developed to take care of major changes in reflectivity that take place when transversing from a hole to a slot. A method should also be devised to detect and record the distance between the signals, and to provide an X - Y plot of the leading edge of the crack as it propagates. This is really the final answer to the monitoring of fatigue crack growth during fatigue testing.

INTRODUCTION

With advancements in material technology, a greater emphasis has been placed on fatigue characteristics of materials, necessitating a very tedious, costly, testing procedure to obtain fatigue data. Present methods require telescopic observations of the fatigue crack as it propogates and the recording of the data. An automated system is needed to reduce the manpower required and to provide a more economical test. A program was therefore initiated by NASA for the "Development of Nondestructive, Automatic Techniques for Monitoring and Recording Fatigue Crack Growth."

The purpose of this investigation is to develop a methodology that will utilize ultrasonic waves and a water coupled ultrasonic tracking probe to automatically monitor and record a fatigue crack with a resolution of 0.010.

SINGLE TRACKING PROBE SYSTEM

General

The tests and investigations that have been conducted during this program have shown the feasibility of automatically tracking the leading edge of a machined slot or a crack with a single moving transducer. With further development the system could be adapted to monitor two directions. Detection of the X and Y coordinates would provide a recorded profile of the crack across the face of the fatigue specimen as it propagates.

An ultrasonic system consisting of water coupled angle transducer producing a surface wave and a back reflector plate to produce a reference signal have been investigated. Tests have shown that increments as small as 0.001 inch can be detected. Basically, the system splits the sound beam so that a portion of the signal is reflected from the edge of the crack and the other portion of the signal is reflected back from a reflector plate. See Figure 1.

The two reflected signals are compared on the scope screen and then balanced against each other. The reflected signal from the reflector plate (back signal) is used as a reference signal and is the signal compared with the crack reflected signal (Figure 1, scope trace B).

As the crack length increases the crack reflected signal also increases and the back reflected signal decreases since it is being blanked off by the crack (Figure 1, scope trace C). By comparing the two signals on error voltage can be obtained to operate a servo motor and thus move the transducer to maintain a balanced signal mode.

Tests have shown that the repeatability of the system is excellent and that the same basic results are obtained from one test to another. This is not to say that exact locations were indicated; there were location errors of the order of 0.050 inch within the first 0.100 inch of machined slot. The same error is recorded each time

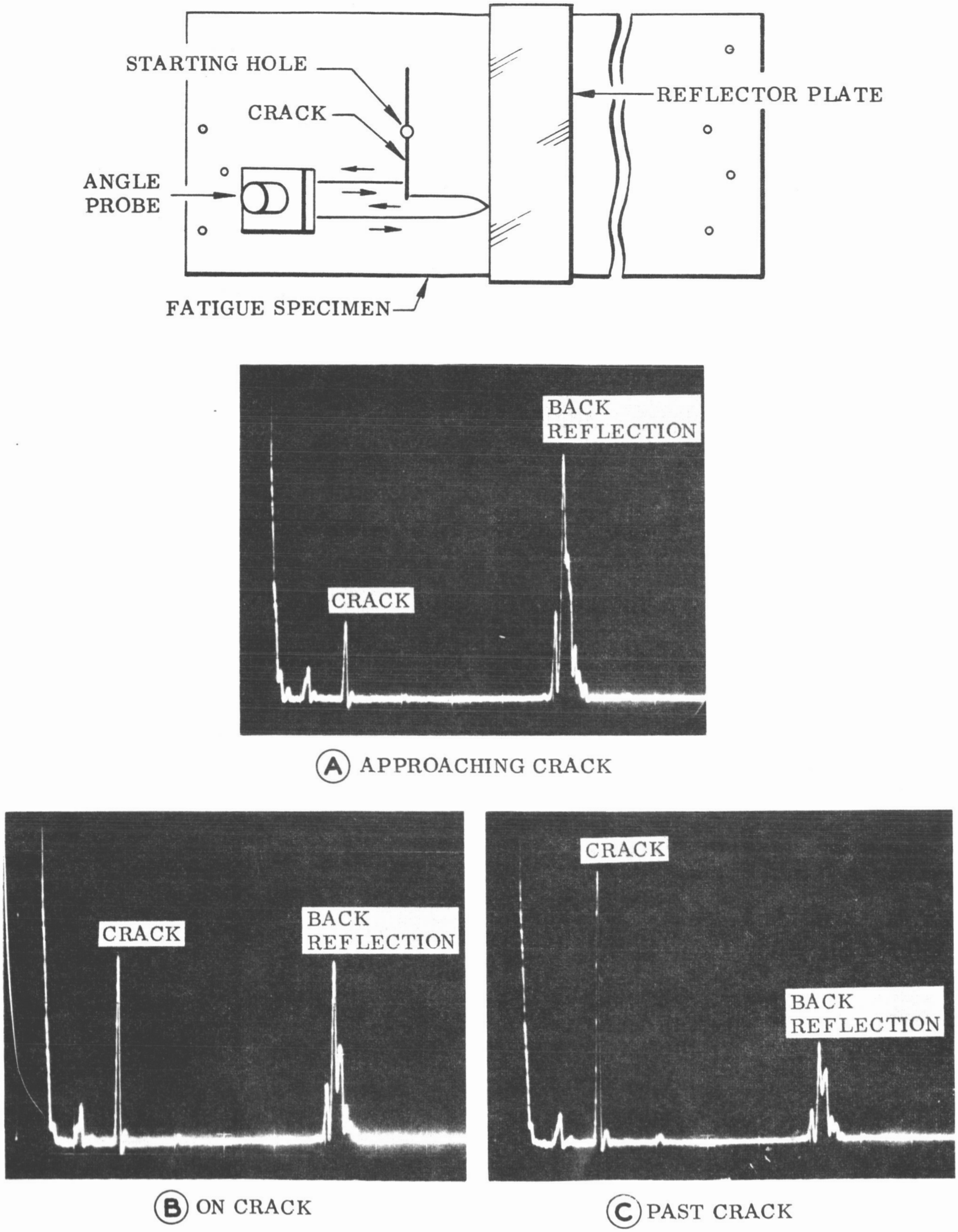


Figure 1. Surface Wave Back Reflected Monitoring System

however, making it possible to introduce a correction factor which will compensate for this error. The causes of this error will be discussed in subsequent sections. After the first 0.100 inch of machined slot location errors on the order of 0.010 occurred which is the tolerance called for in the contract.

This final report covers the following areas of investigation.

1. Tuning procedures.
2. Analysis of reflectivities starting from a round hole.
3. Comparison of various signal amplitudes for different crack orientations.
4. Investigation of various ratios of signals and their effect on linear positioning.
5. Comparison of response curves and dimensional error.
6. Design of Ultra-Sonic Fatigue Crack Detector.
7. Investigations to determine the accuracy of location of a machined slot by manual and servo operated techniques.
8. Electronic systems description:
    1. Operation of the Electronic System
    2. Trigger
    3. Dual Gate
    4. Delay Line
    5. Signal Conditioning Unit
    6. Servo Control and Drive Motor

TUNING PROCEDURE

System Components

The optimized physical setup on a test specimen is shown in Figure 2. A 0.156 inch diameter hole was drilled into the center of a 1/8-inch-thick 2024-T3 aluminum alloy specimen to simulate a crack starter notch. A 1/8-inch thick reflector plate was clamped to the specimen on one side of the hole. This reflector plate extended across the width of the specimen and was ultrasonically coupled to the specimen by a film of vacuum pump oil. An ultrasonic transducer unit was mounted on the opposite side of the hole to the reflector plate. The unit consisted of a 1/2-inch diameter. 5.0 MC Zirconate crystal transducer, a hollow acrylic-plastic block and a servo-drive motor. An O-ring gasket was used to seal either end of the column of water that coupled the transducer ultrasonically to the specimen. The transducer was pivot mounted so that the injection angle of the ultrasonic wave could be varied. Dimensions "A" and "B" are the optimized dimensions found in this investigation. The dimension "A" can be set as shown, but dimension "B" can require a slight variation to produce a clean reflected signal.

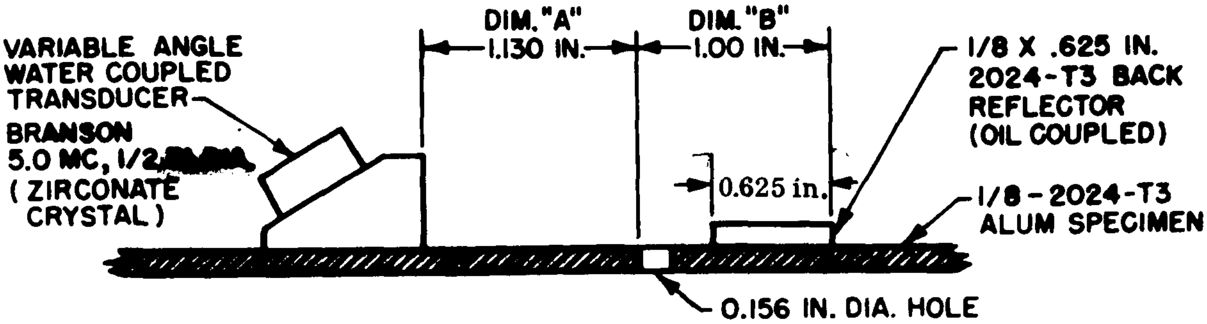


Figure 2. Setup for the Two Signal System

A Sperry Products UM-721 reflectorscope was usually used to excite the transducer and to display the received signal. This equipment has an adjustable pulse output which was used to trigger the electronic gating portion of the system.

In order to optimize the performance of the monitoring system the following tuning procedures were followed after mounting the transducer system and water-coupling to the specimen. (See Figure 2.)

Initial Tuning Adjustments

1. Set the frequency knob for 2.25 MC. Even though a 5 MC cyrstal was being used this setting and the use of the fine tuning knob produced the cleanest reflected signal. The frequency depends on how all of the impedances of the systems are matched.
2. Adjust the pulse length to maximum. This provides maximum power to the transmitted pulse.
3. Sweep can be adjusted to any desired display.
4. Move transducer to pickup hole signal.
5. Turn the pulse tuning knob to obtain maximum signal. This knob is a vernier control for tuning the frequency for best overall matching of the impedances of the system.
6. Adjust coarse sensitivity switch to X-1 position and fine sensitivity knob for approximately 7 divisions high signal in the video screen.

7. Adjust the reject knob to clean up the signal so that only the initial pulse and the desired echo signal is present. The reject function removes the noise portion of the signal.

<u>Final Tuning Adjustments</u>

1) If the signal shape does not look like that of Figure 3, further tuning is indicated. Three parameters can be varied to accomplish this. a) Adjust the angle of the transducer to produce as clean a signal as possible. b) Adjust the pulse tuning for maximum signal. If the signal still does not appear as in the figure some movement of the transducer toward or away from the starting hole should produce the proper shaped signal. Do not deviate too much from the dimension given. c) Readjust the other two variables if required, a and b.

2) Couple the back reflector plate using vacuum pump oil to the specimen. Move the plate back and forth near the dimensions given to produce two signals as shown in Figure 4. Some retuning of the transducer angle and the pulse tuning may be necessary to produce the best overall response.

3) To check the tuning procedure rock the pulse tuning knob clockwise and counterclockwise with a video display of a balanced signal. Both peaks of the signal should go up and down together. If they move opposite to each other, tune to another location with the pulse tuning knob, or change the angle of the transducer to produce signals which will peak together.

These adjustments were required only on the first setup; after that, only minor adjustments were necessary when mounting a new specimen.

One other check should be made to identify the signals and to be sure the signals on the video display are the ones of interest. To identify the signals simply wet a finger and move the finger across the specimen to interrupt the signal. By this method each signal can be interrupted separately and identified.

ANALYSIS OF REFLECTIVITIES

Typical plots of reflected signal amplitudes against transducer position for the hole and the reflector plate are shown in Figure 5. This plot will be referred to herein as a response curve.

These response curves were obtained by moving the transducer across the width of the specimen from one edge to the other.

In order to track a crack or notch (machined with an 0.060-inch diameter end mill to simulate a crack) coming from one side of the central hole, the transducer was placed at point A. (Figure 5) so that the amplitude of the signals coming from the hole and the reflector plate were balanced. The system is now ready to automatically monitor the advance of the machine notch.

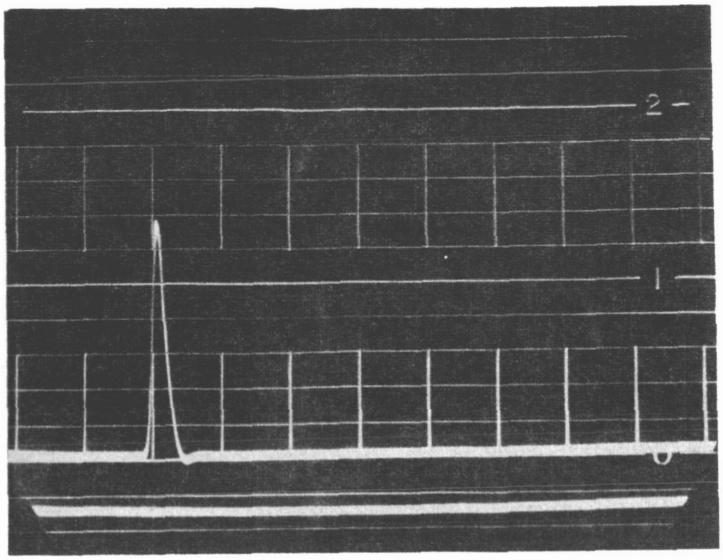


Figure 3. Properly Tuned Hole Signal

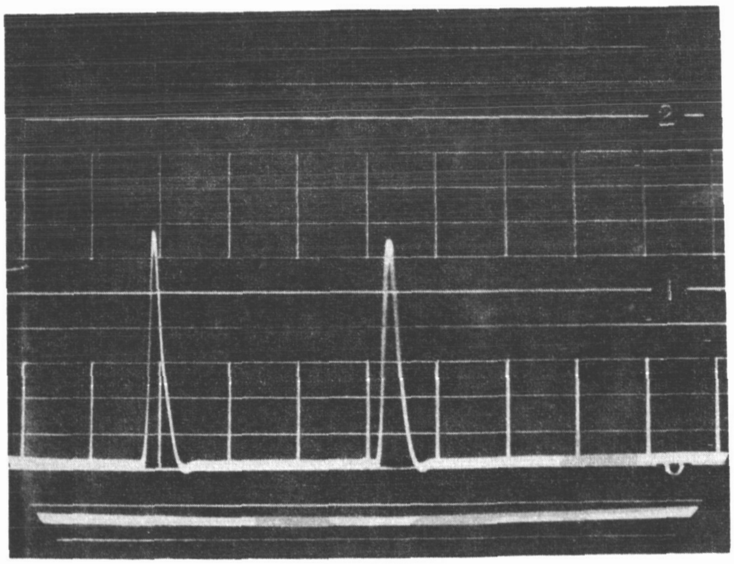


Figure 4. Properly Tuned Reflector Signal

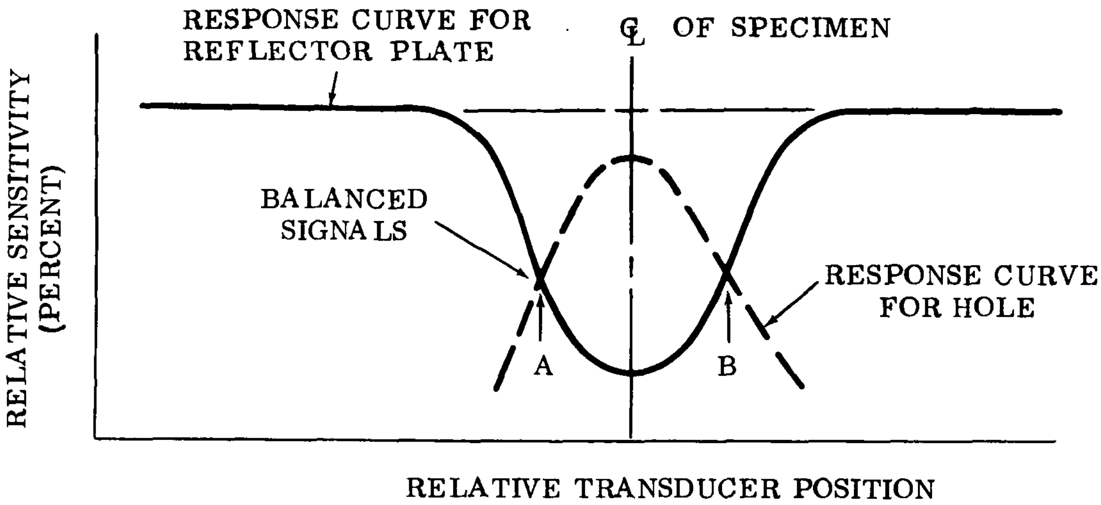


Figure 5. Typical Hole and Back Reflector Response Curves

The amplitude of the signals reflected from the notch-hole combination and from the reflector plate changed and became unbalanced as the notch was cut into the side of the hole. This unbalance produces an error voltage which actuates the electronic system (to be described subsequently) controlling the servo motor that moves the transducer parallel to the notch until the signals are balanced again. The movement of the transducer required to restore balance corresponds to the advance of the machined notch.

An analysis of the response curves when going from a circular hole to the notch-hole combination was conducted. Measurements for the first .100 inch proved most interesting.

A response curve was obtained for the hole and back reflector plate as described in the preceding section. A 0.030-inch long notch was machined into the side of the hole and the transducer translated to produce the new hole-notch combination response curve (Figure 6). Rebalancing of the signals required .030-inch movement of the transducer over the length of the milled notch. The amplitude of the new balance point (.030-inch) was somewhat lower than the amplitude of the balanced signal with no-notch point "0". This was due to increased scattering of the reflected signal off the notch-hole combination since the .030-inch radius coming from the hole does not produce a flat surface to reflect the signal back to the transducers.

The notch length was increased by another .030-inch and the transducer unit again moved to obtain a new response curve (Figure 7). Rebalancing of the signals required a .070-inch movement which was .040-inch longer than the increase in notch length. Two things combined to produce this .040-inch error. First, there was a disproportionate increase in the amplitude of the signal reflected from the notch-hole combination. A .030-inch long flat surface of the .060-inch long notch is a better reflector than the curve surfaces of the .030 inch notch hole combination. Second, the

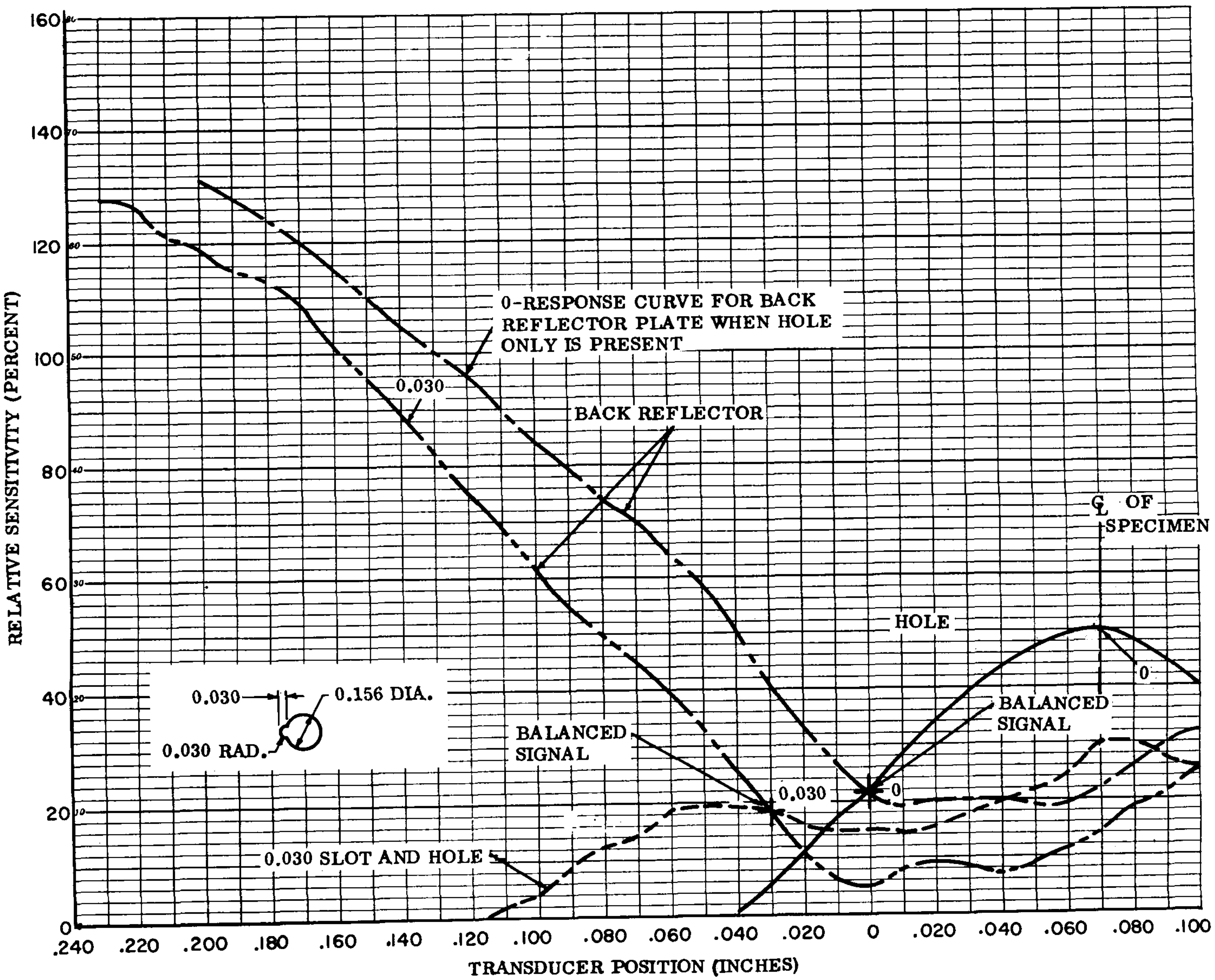


Figure 6. Reflectivities of 0.156-Inch Diameter Hole and Different Lengths of 0.062-Inch Wide Machined Slot (.030)

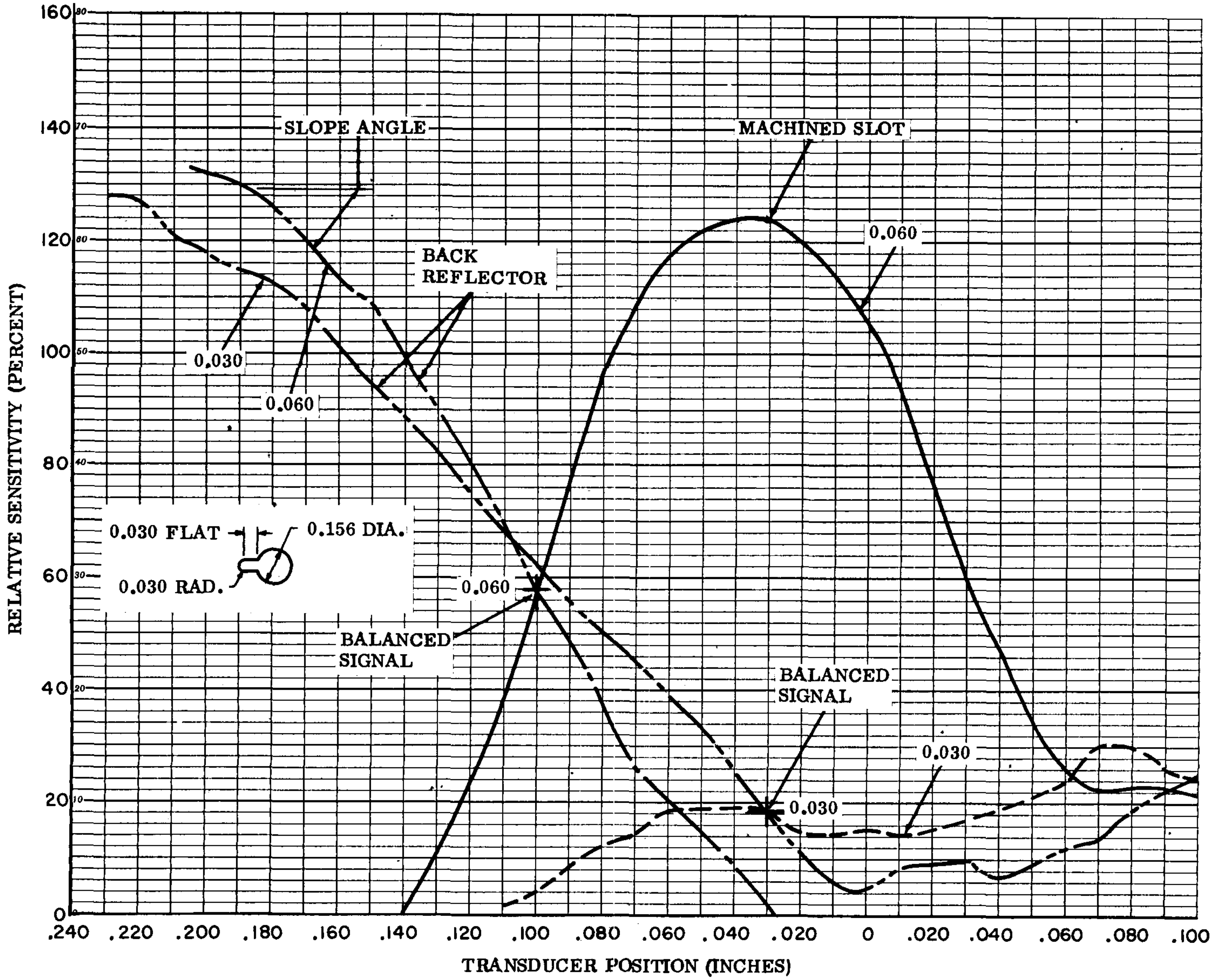


Figure 7. Reflectivities of 0.156-Inch Diameter Hole and Different Lengths of 0.062-Inch Wide Machined Slot (.060)

slope angle of the response curve for the reflector plate was increased. The smaller radius at the leading edge of the notch produces less scatter of the signal going to the reflector plate than does the hole or the .030-inch notch-hole combination. Thus, the signal energy reaching and reflected from the reflector plate is increased.

The notch length was increased by another .030-inch and the transducer moved to balance the reflected signals, Figure 8. This movement was .032-inch which indicated .002-inch location error in the transducer movement from a total notch length of .060 to a length of .090-inch and an accummulated error of .042-inch. Additional .030-inch cuts were made and the average error from movement to movement was ± .005-inch (Figures 8, 9 and 10). The errors were not cumulative however, and at a total notch length of .270-inch the total error was .033-inch.

Thus once the area near the starting hole had been cleared the measuring accuracy was ± .005. Duplicate tests were conducted with other specimens and produced the same results.

Figure 11 shows the overall amplitude changes of the signals when starting with a .156-inch diameter hole and cutting a slot. As can be seen in the first .030-inch the hole and slot combination of reflection decreases due to scattering of the signal as explained above. Note also that the back reflector amplitude does not change very much and that the amplitude of the balanced signal is an average of the two signals. After the .030-inch region the hole-slot combination increases in amplitude and the slope of the leading edge (smaller radius) of the slot produces less scattering of the signal which in turn increases the overall efficiency of the system with a slight general increase in the signal height of the back reflector.

SIGNAL AMPLITUDE VERSUS CRACK ORIENTATION

A study was made to determine the effect of fatigue crack orientation on the reflected signals from the crack and the reflector plate. A fatigue cracked (2024 T3 aluminum alloy) specimen was installed in the test setup and the transducer moved across the specimen along the path (shown in Figure 12a) which is at an 8 degree angle to the path of the fatigue crack. The resulting response curves are also shown in Figure 12a. The specimen was then rotated to make the fatigue crack parallel to the transducer movement and a response curve was obtained (Figure 12B). The amplitude of the balance signal point increased due to the increased reflection from the fatigue crack in the parallel case. This was expected since there is intrinsically more scattering of the reflected signal in the 8 degree angle case.

The amplitude was sufficient at the 8 degree angle, however, to assure that the monitoring system would operate properly.

Since most of the test work was done utilizing a machined slot to accurately locate the end of a slot a reflected signal amplitude, comparison of a 7 degree angled fatigue crack and a straight machined slot was conducted (Figure 13). The machined slot reflected signal amplitude is much higher that either the straight fatigue crack or the angled fatigue crack cases.

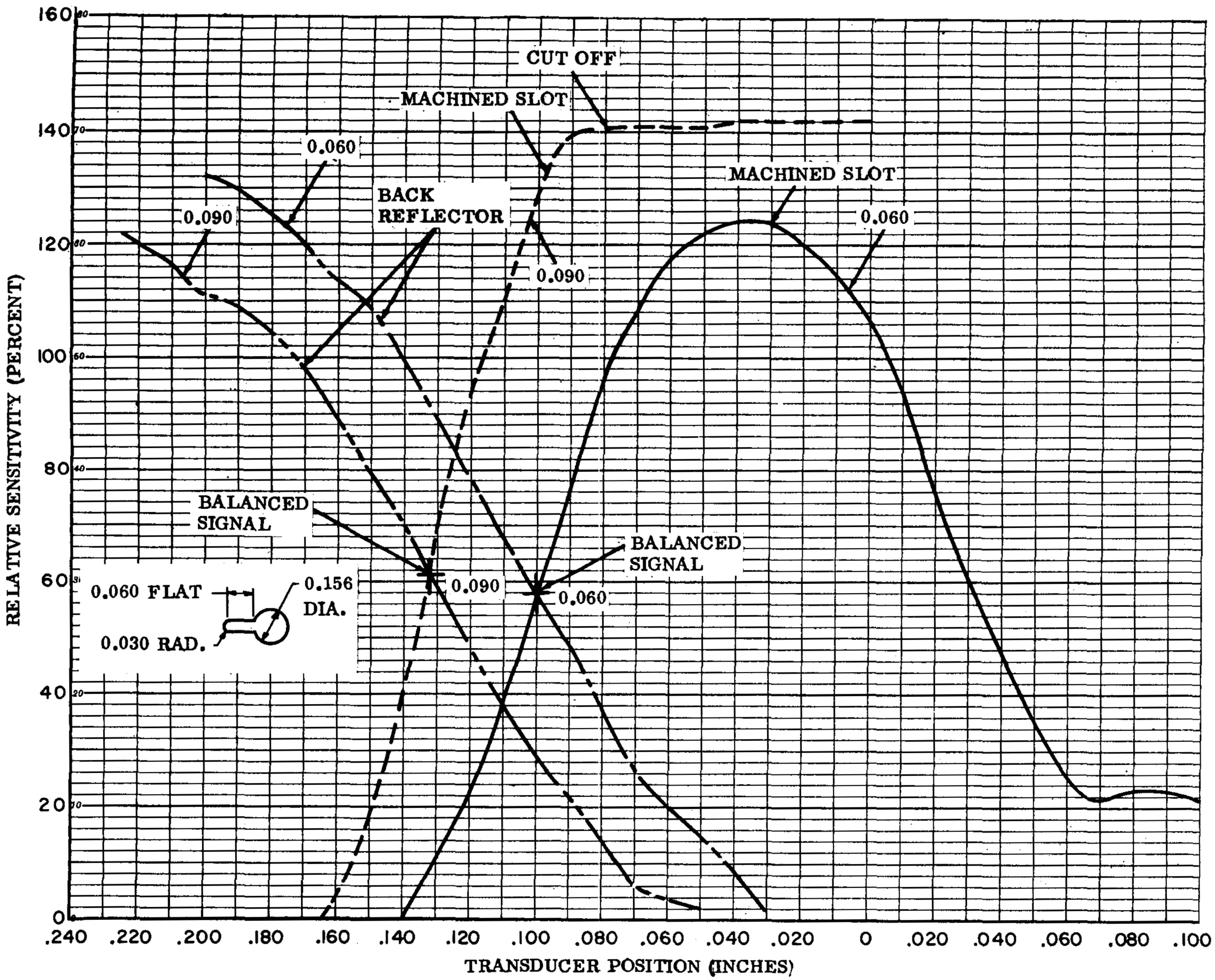


Figure 8. Reflectivities of 0.156-Inch Diameter Hole and Different Lengths of 0.062-Inch Wide Machined Slot (.090)

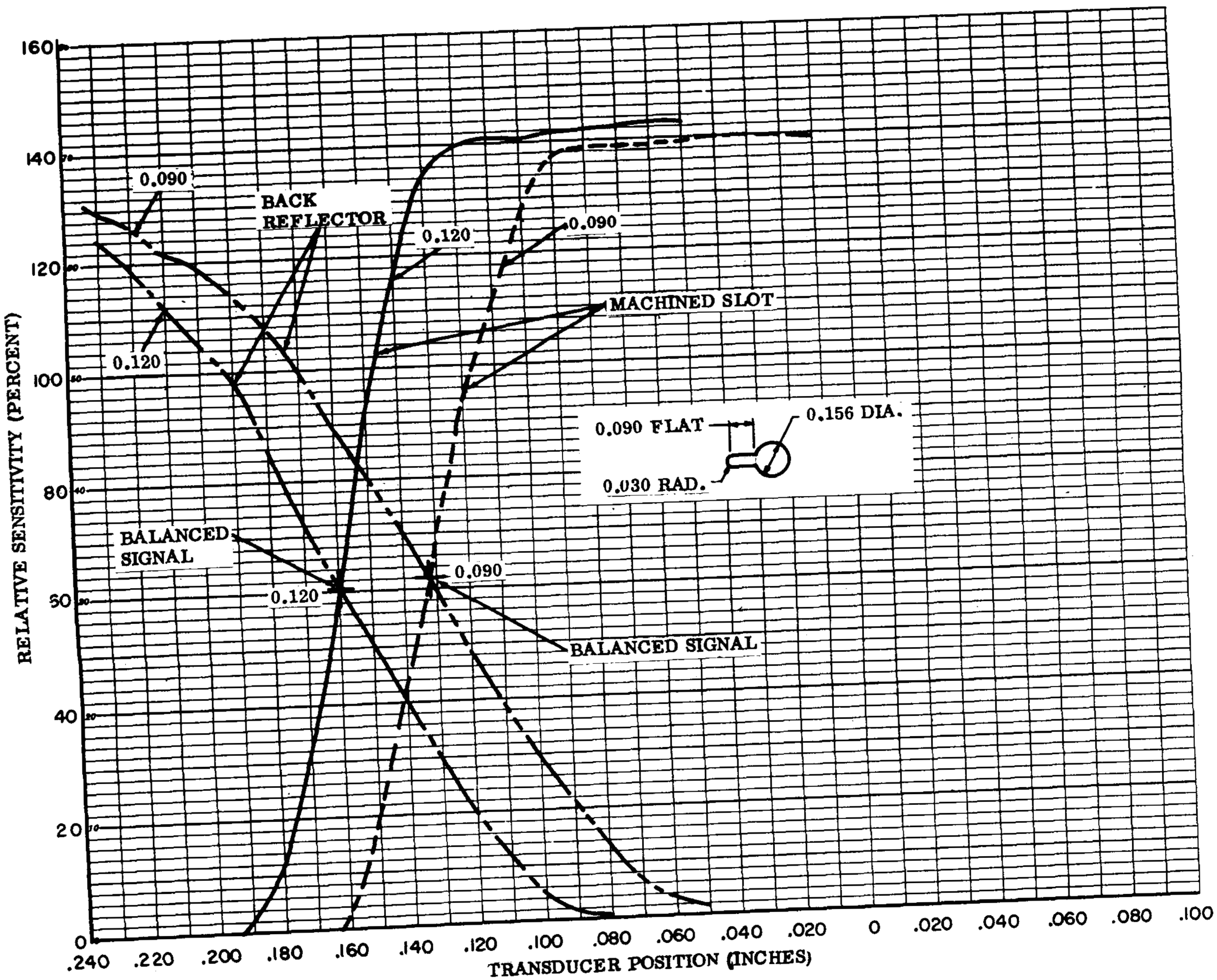


Figure 9. Reflectivities of 0.156-Inch Diameter Hole and Different Lengths of 0.062-Inch Wide Machined Slot (.120)

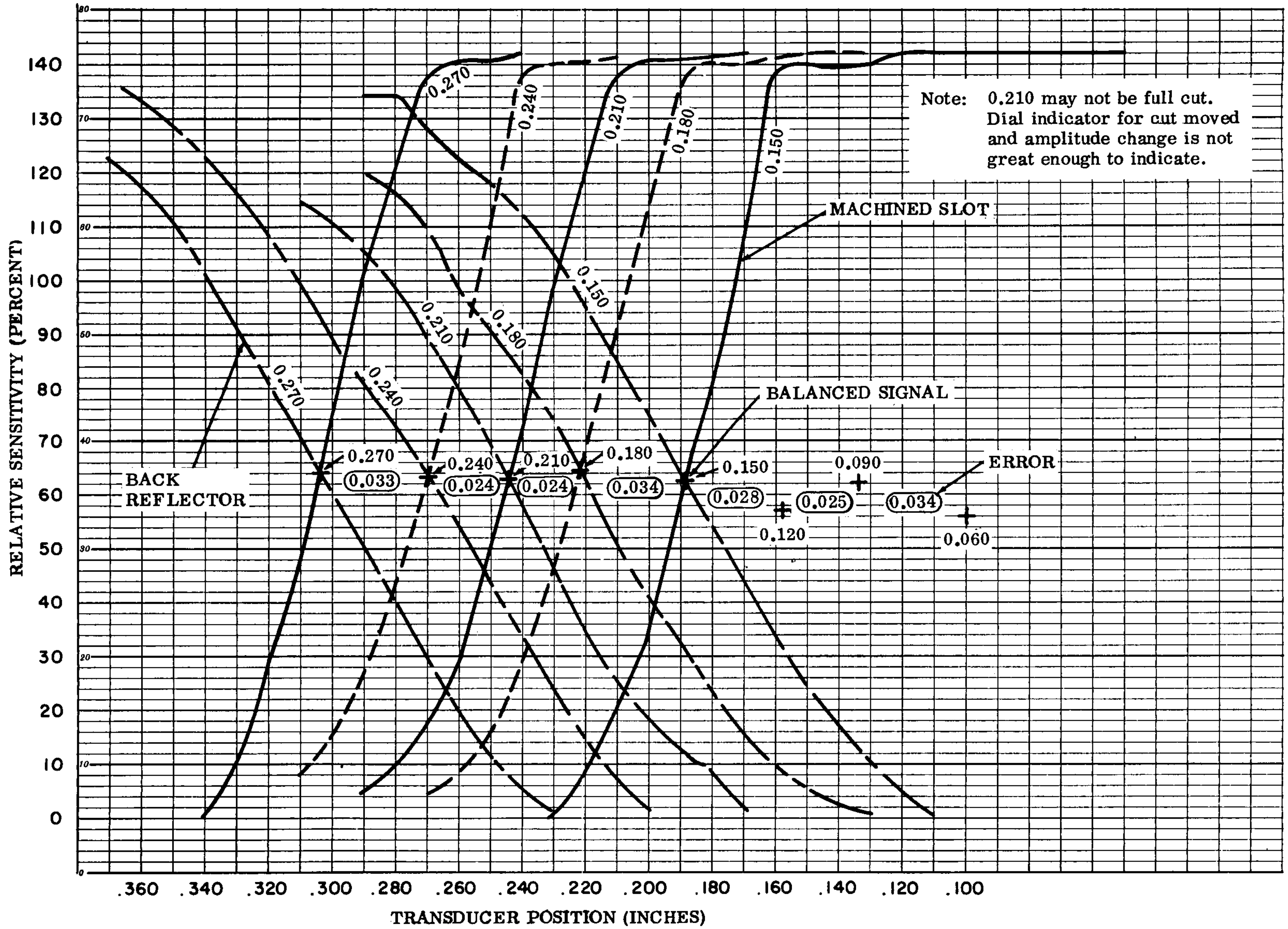


Figure 10. Reflectivities of 0.156-Inch Diameter Hole and Different Lengths of 0.062-Inch Wide Machined Slot (.270)

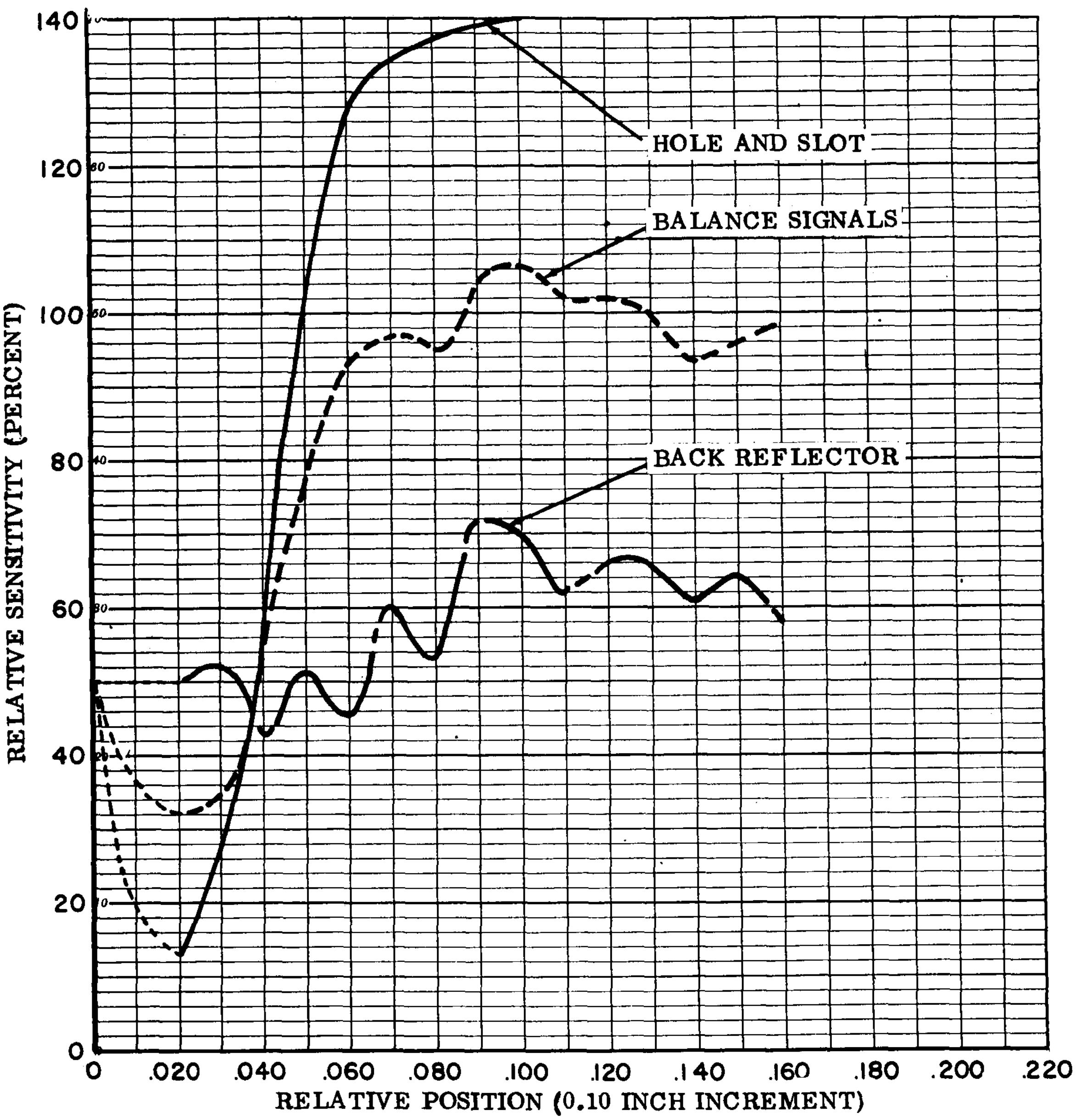


Figure 11. Signal Amplitude Change from Round Hole to Slot Configuration

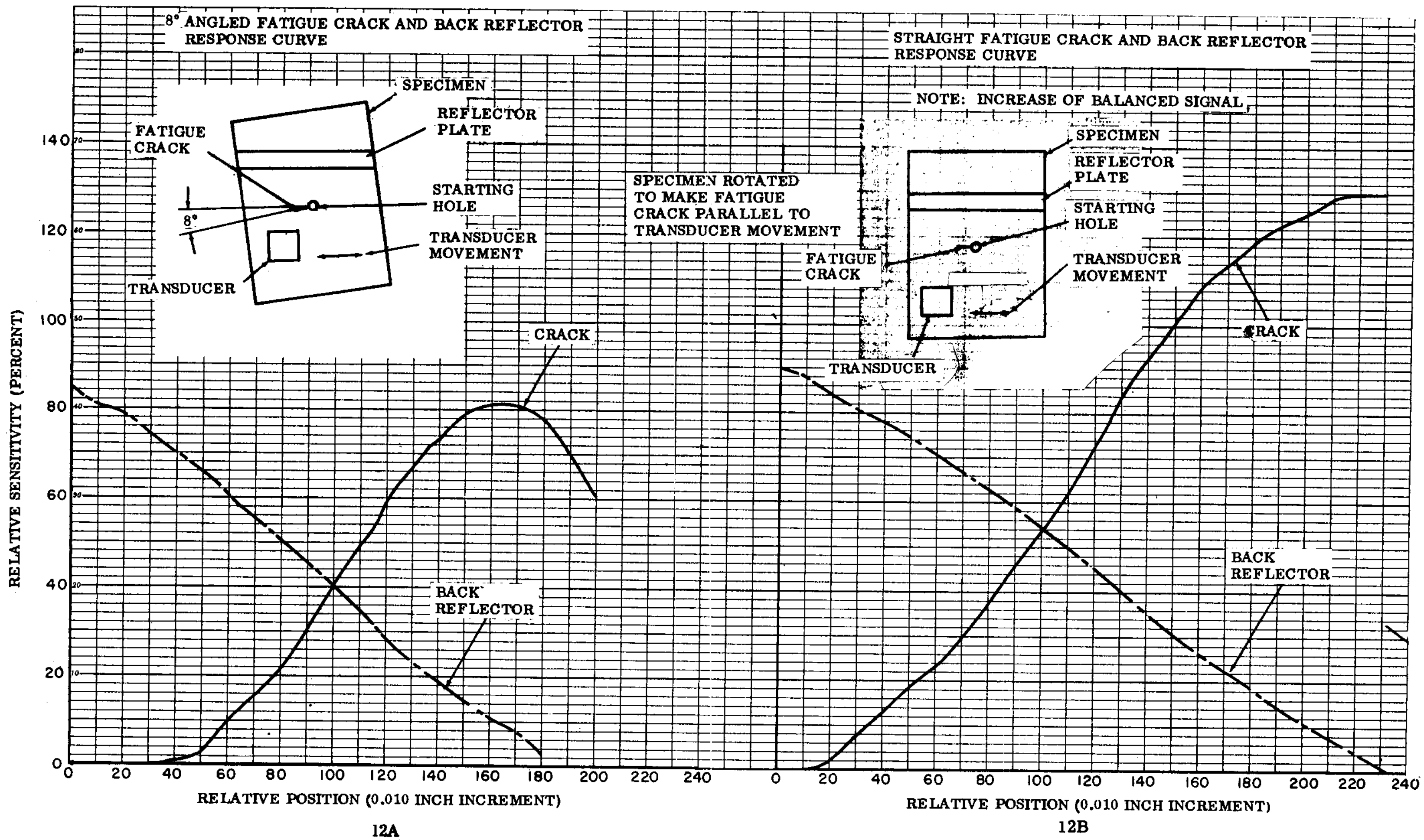


Figure 12. Comparison of Angled Fatigue Crack and Straight Fatigue Crack Response Curve

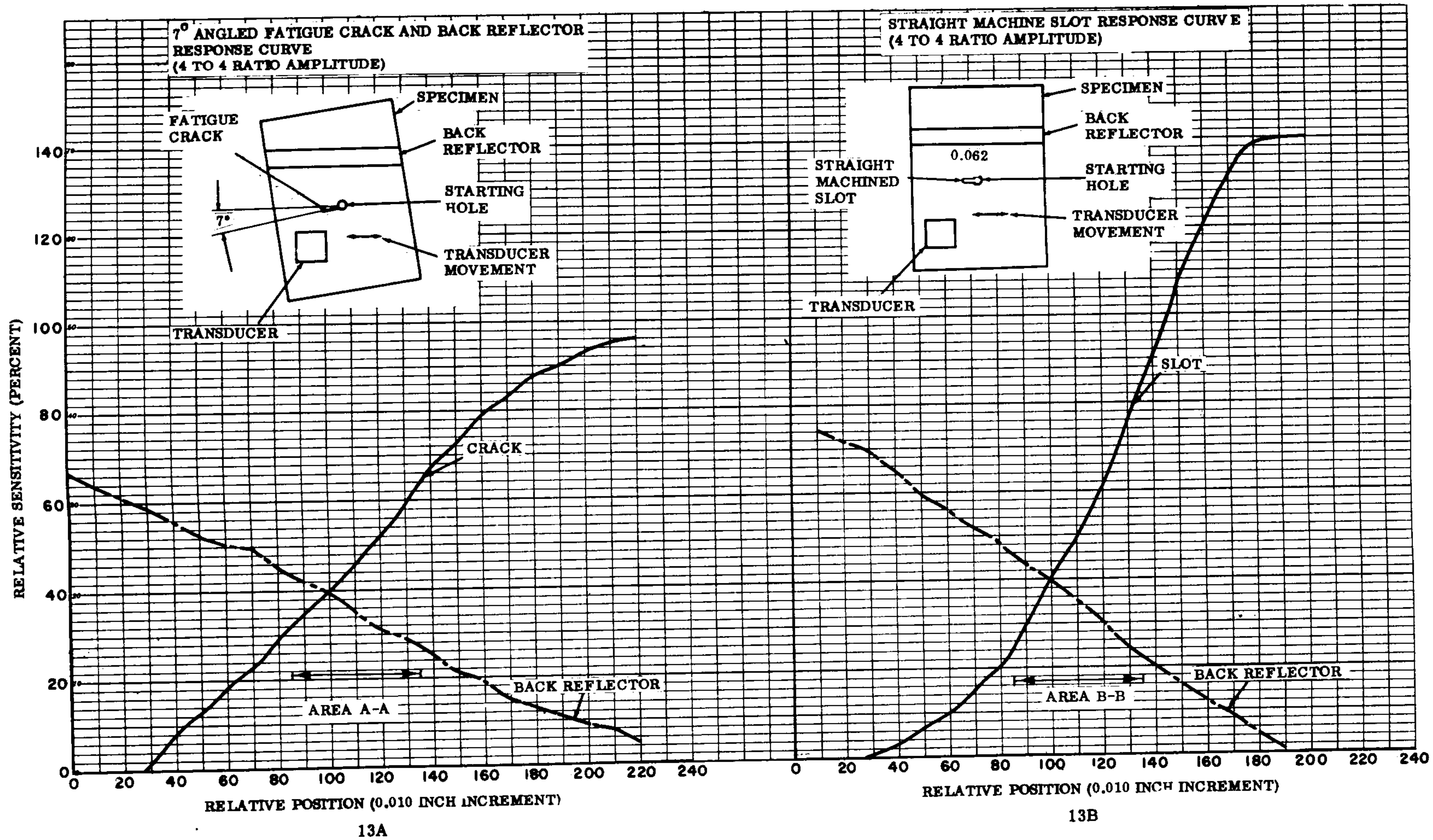


Figure 13. Comparison of Angled Fatigue Crack and Straight Machined Slot Response Curves

SIGNAL RATIOS VERSUS TRANSDUCER LOCATION

Investigations of various starting signal ratios and the resultant effect on the linear positioning of transducer are described in this section. The starting ratios referred to here are the changes of reflectivity when starting with a machined slot, straight fatigue crack or an angled fatigue crack. The back reflected signal can be maintained at a relatively constant amplitude for all of these conditions.

From the beginning of the investigation of the transducer positioning versus the actual slot length tests, a record of the balanced signal amplitudes and the incremental positions of the transducer were made. It was found that even though the balanced signal amplitude remained relatively stable there were some errors in the actual location of the end of the machined slot, and there was an additional factor other than balance, that produces inconsistent results.

Increasing or decreasing the balanced-signal amplitude of the normal hole to back reflector response curve with the sensitivity control on the ultrasonic unit did not change the location of the transducer and the indicated location.

Further investigation has shown that the actual indicated error of the transducer position is caused by a reflected amplitude change between the starting hole and the slot or fatigue crack, which in turn, upsets the original balanced signal condition. That is to say, the back reflected signal amplitude remains constant and the slot reflectivity increases with a resultant signal increase. This requires repositioning the transducer for the balanced signal; but even more important is the amplitude ratio change between the slot and back reflected signals. Starting with the .156-inch diameter hole the system can be set up so that the hole and back reflector maximum signals are of equal amplitude. The balancing of these two signals defines a particular location for the transducer. As the slot is cut the reflected amplitude coming from the slot increases approximately three times over that of the original starting hole. This now changes the signal ratio from 1:1 to 3:1. This ratio difference drives the transducer ahead of the slot with a resultant error in this case of approximately .050-inch. This error will be less when going from the hole to the fatigue crack since their amplitudes are more comparable.

After reaching a stable balance signal with the three to one ratio of amplitude, there is another error introduced with small changes in amplitude and this is explained in the following example.

Taking the balanced signal portion of the response curves shown in Figures 13A and 13B and increasing the linear dimension scale, the difference in error can be shown (Figure 14). Assuming the crack or slot amplitude at the .010-inch dimension to have a balanced signal condition, then the back reflector signal amplitude must be the same. Draw a line between these two points, and where the line crosses the base line will be the actual position located by the transducer. As can be seen, the greater the ratio difference between the crack and back reflector signals the greater the error. This error is only introduced, however, when there is an amplitude ratio change. If there are no changes in either of the reflectivities except for the propogation of the crack, the ratios just discussed will not be important. It is important, however, to

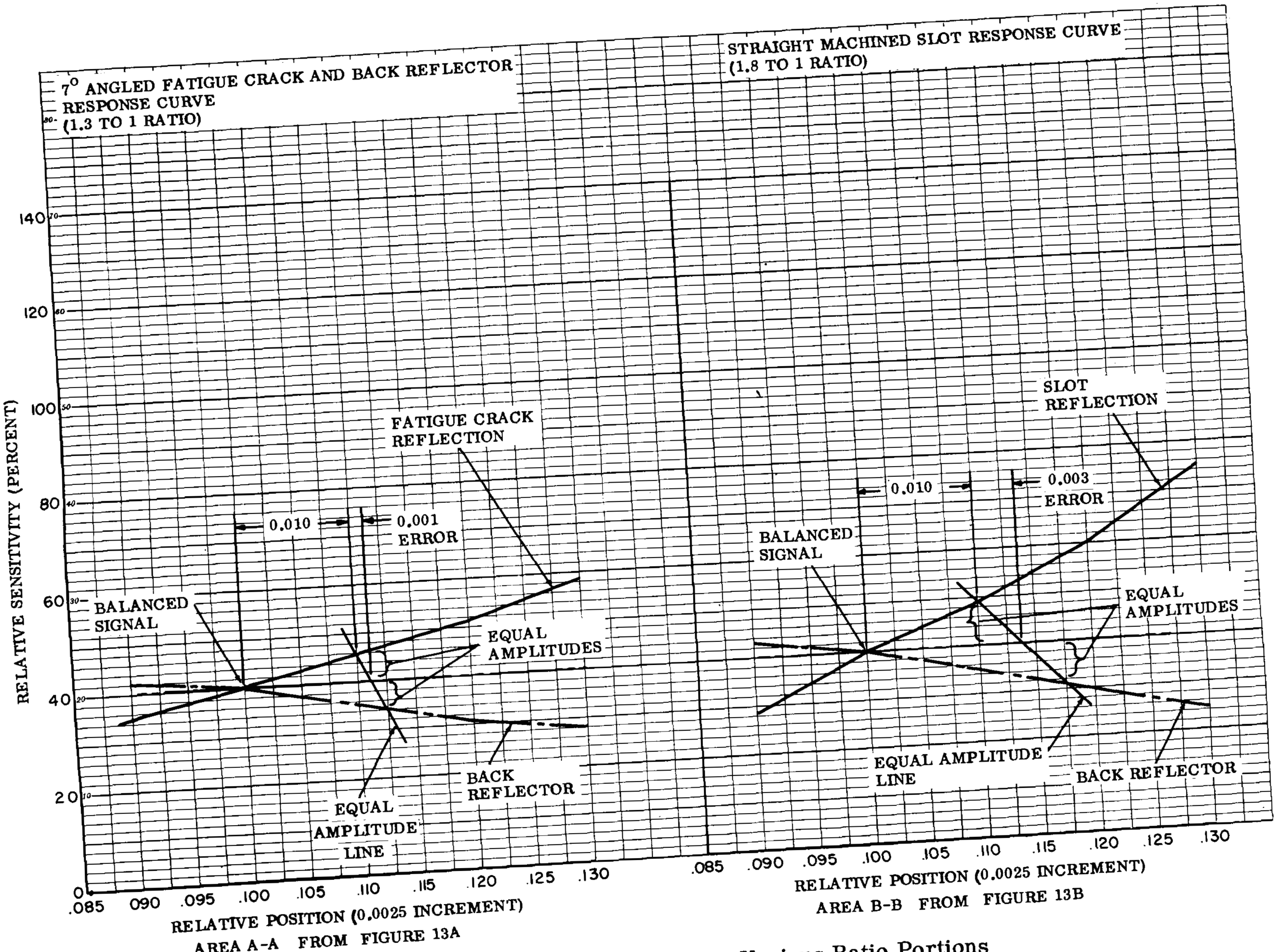


Figure 14. Comparison of Errors Caused by Various Ratio Portions

have a comparable amplitude between the fatigue crack and the back reflected signal to minimize error.

RESPONSE CURVES VERSUS DIMENSIONAL ERROR

A comparison was made between response curves and the total indicated dimensional error along with an investigation of the effect of cutting first one half of a slot and tracking it with the transducer, then changing direction and cutting the other half of the slot and tracking it. Figure 15 shows a response curve using a 0.156-inch diameter starting hole. Above the response curve is a graph of the total dimensional error versus the length of slot, for a slot .600-inch long. As can be seen in the first .100-inch there is an initial error of .050-inch. In the next .500-inch of slot length there is an additional plus .013-inch error introduced. Figure 16 shows the other side of the response curve after having cut the slot on the one side. Note the increase in the hole-notch signal. This increase is due to the slot; normally there is signal in this area but it is being reflected from the back reflector not the slot. In this case there was a total error of 0.045-inch in the first .100 inch followed with a minus .006-inch error for the next .500-inch of slot length.

This test proved that even though the starting signal amplitude reflected from the hole increased for the second slot that this has no effect on the initial error area and that two simultaneous cracks can be propagated without affecting the results. There was no apparent correlation between the response curve shape and the amount of total dimensional error obtained.

ULTRASONIC FATIGUE CRACK DETECTOR DESIGN

An ultrasonic fatigue crack detector has been designed and manufactured to clamp and to drive the water coupled transducer across the face of the specimen. (See Appendix.) With further development work this design could be miniaturized to reduce the weight and to increase the sensitivity of the response of the system.

For this design it was decided that the back reflector be a separate part oil coupled and clamped to the specimen. It is envisioned that the reflector plate could be attached to the transducer unit frame to locate the reflector and reduce setup requirements. Some research was also done with a water coupled reflector similar to the design of the transducer end, but in place of the transducer was an adjustable angle aluminum rod and this assembly was maintained opposite to the transducer end to act as the reflector plate. This reflection system produces very clean reflected signals and is very selective, requiring fine adjustment of the incident angle of the reflector face. The reflector can be used two ways; it can be attached and moved with the transducer, or it could be a long stationary reflector. The moving type might produce less signal amplitude errors since it sees the same reflected surface all the time. Further research would have to be accomplished to prove out an operating system.

Provisions have been made to vary the angle of the transducer for optimizing the tuning procedure. It was also found necessary to change the angle slightly when changing the gauge of material. This is especially true when changing to light gauges and when changing from the aluminum to the titanium alloy.

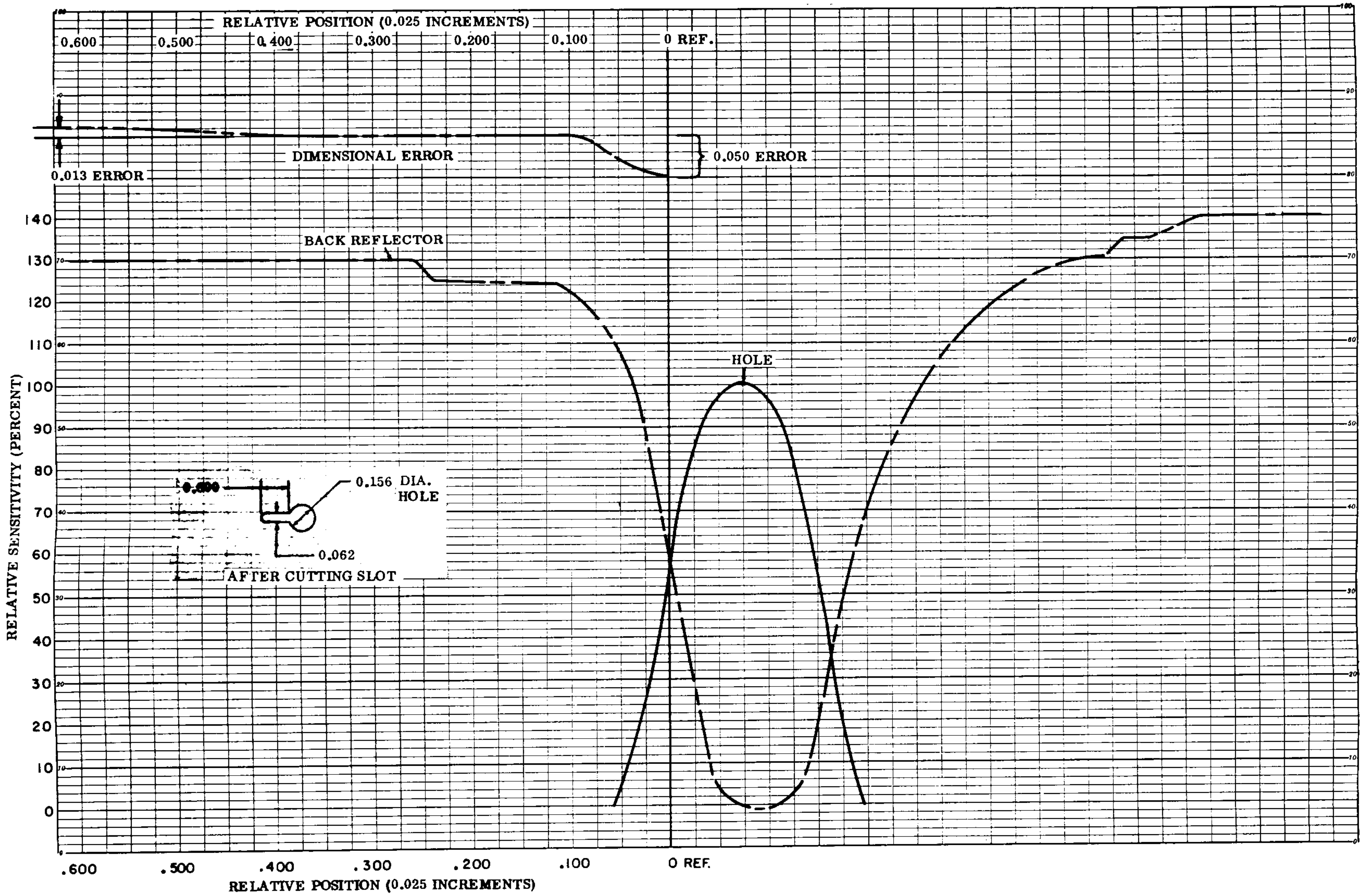


Figure 15. Response Curve Starting with 0.156-Inch Diameter Hole and Dimensional Error Pattern

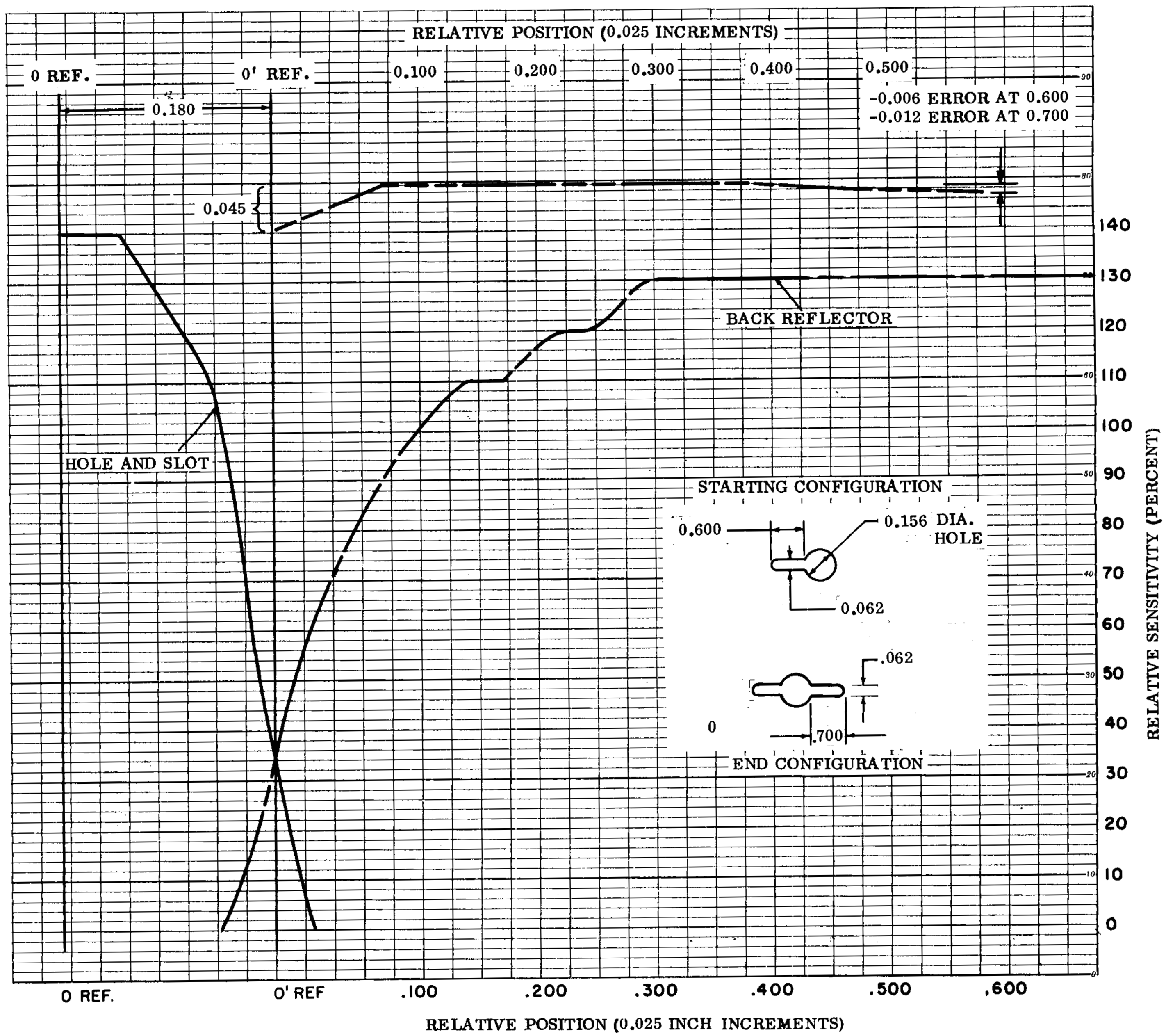


Figure 16. Response Curve of 0.156-Inch Diameter Hole with Half Slot and Dimensional Error Pattern

In order to reduce the bending loads on the fatigue specimen as much as possible, the drive system, limit switches, and position indicator are mounted remotely. A flexible shaft is used to couple the drive system and the transducer screw together.

LOCATION ACCURACY

General

Investigations to determine the accuracy of the location of the end of a machined slot by the water coupled angle transducer system have been conducted. With further development work closer toleranced locating accuracy could be accomplished. Some of the items reported in this section are presented only as observations with no conclusions drawn.

Variations in indicated location of the end of a machined slot of .002 to .003-inch were observed when recording a position immediately after cutting the slot or after waiting for a period of time. The variation was traced to a temperature rise created by the .001-inch incremental machining of the .010-inch long slot.

When using the UM-721 reflectoscope it was observed that the level at which the rejection system was tuned as previously described could effect the linearity of the transducer movement in the first .100 inch. The transducer position indicated could actually go opposite in direction to the direction of the machining of the slot and then suddenly return to the correct location and follow the rest of the machining of the slot normally.

With all the variation noted in the early stages of the slot changing from the starting hole the system was repeatable and if no further work was done the system could be used by putting in correction factors at the required positions to correct for the errors. Further development to correct this condition is advisable, and would make the system fully automatic and a direct reading instrument which anyone could use.

Static Test

Static tests were made to determine dimensional accuracy and correction techniques for a single angle probe system to manually follow the machined slot.

Tests were setup to compare results obtained from the ultrasonic reflectoscope and signals which were processed through the dual gate, delay line, and signal conditioners and displayed on a dual beam oscilloscope. The electrical schematic is shown in Figure 17.

Comparison of the signal traces is obtained with a Tektronix type 555 dual beam oscilloscope (two gun) with individual time base units. The signal preamplifiers are type CA, dual trace units, thus giving a capability to display four tracers. The preamps were operated in the alternate mode rather than chopped to give a smooth trace.

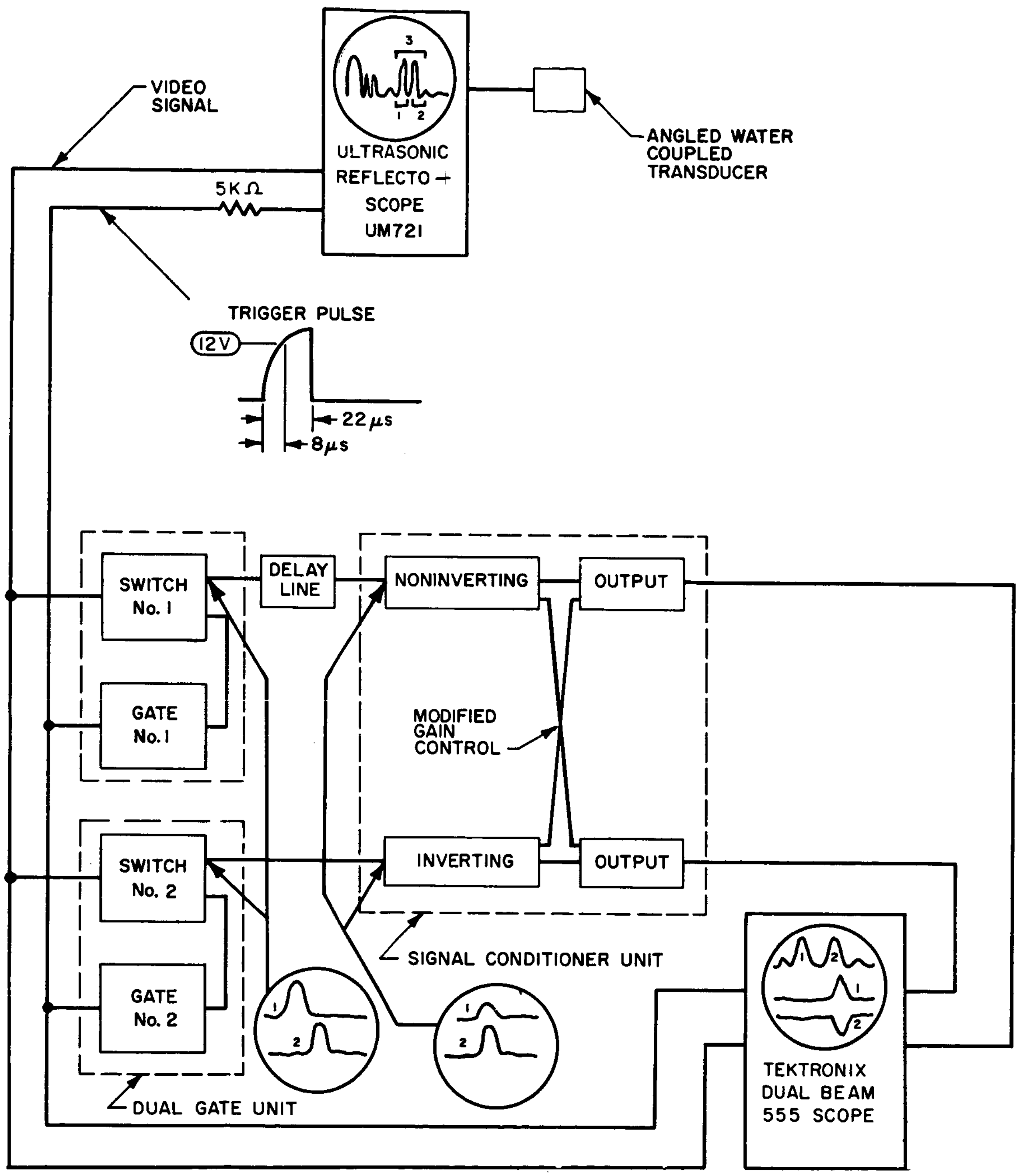


Figure 17. Dual Gate, Delayline and Signal Conditioner Test Setup

Jitter free triggering required the use of external trigger mode. The trigger pulse (+ 12V) obtained from the Reflectoscope was also used to initiate the time gated switches which control two channels of the scope display.

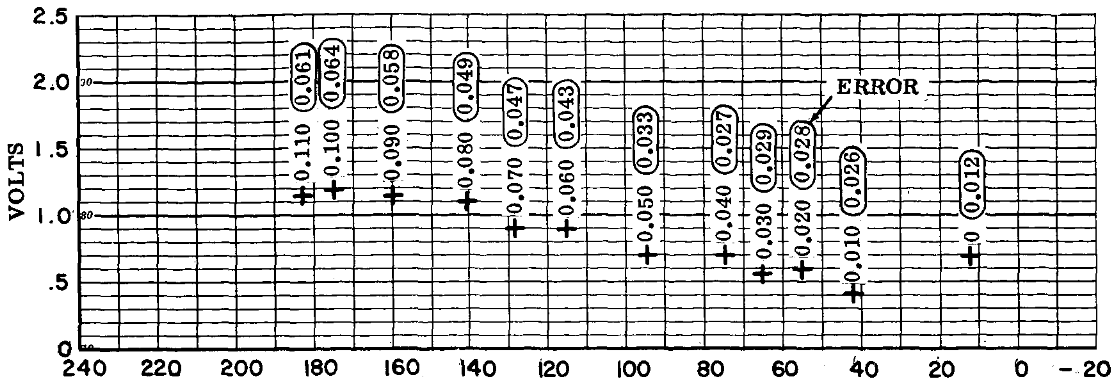
Typical video signals appearing on the Reflectoscope screen (reading from left to right, Figure 17) includes the transmitted signal to the transducer (big bang), extraneous reflection, crack or notch reflections, back reflector signal, and other extraneous signals, such as reflections from the end of the specimen. Only the signals from the crack and back reflector are required (bracketed as area 3). These two signals of interest, (identified as area 1 and 2) are extracted from the video output of the Reflectoscope by the time gated switches. The resultant signals, differing in time relation are shown at the lower left of Figure 17. The leading signal (#1) from the crack then inters the delay line where it is brought into step with the back reflector signal (#2). The two signals now in phase are then fed into the signal conditioning unit, in which the attenuation of the delayed crack signal is corrected and the back reflector signal is inverted.

The two signals are then fed to the oscilloscope for display and comparison with the upper trace Figure 17. The upper trace is the expanded portion (area 3) of the Reflectoscope video display containing the signals of interest.

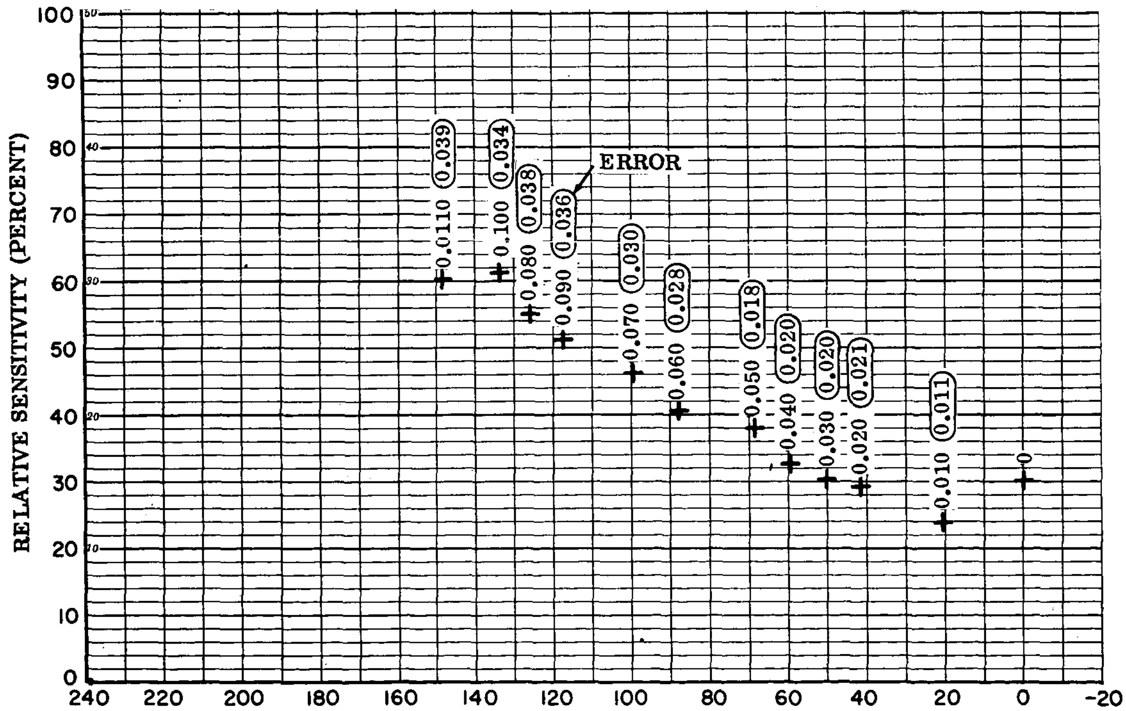
Tests were conducted comparing the two display systems, both starting with balanced signals. The results showed that each produced slot location within .002 or .003-inch of each other which indicates the linearity of the electrical system shown is satisfactory.

Tests were conducted manually following a machined slot as it was incrementally machined and comparing the two display systems, while varying amplification and other conditions of the signal conditioning unit, to provide a correction factor. In these tests variation in signal amplitudes and positioning will be noted on the ultrasonic "Reflectoscope" balance signals curves. This, however, was done purposely since in a balanced constant amplitude condition there are very little positioning variations and there is no requirement for a correction technique.

The first test which was performed, applying a correction factor, had the hole or slot signal applied to the inverted signal channel. This channel has ten time the amplification of the noninverted channel, Figure 18. As can be seen in this test that there was a greater error in the compensated channel. The ultrasonic unit showed errors of .036 to .039 inch after .090 inch of slot, while the compensated system showed errors of .058 to .061-inch. A second test was conducted reversing the channels of the signal conditioning unit in the automatic tracking system and injecting the hole or slot signal in non-inverting channel, Figure 19. This time the ultrasonic unit shows an error of .042 to .048 inch after the first .090-inch of slot, and for the compensated system an error of .021 to .028-inch. The tests show that a correction factor can be applied even when starting with balanced signals. It also has been shown that the correction factor can be reversed by switching channels. With further research a proper correction factor could be selected to provide an exact location which would provide a direct reading and recording system.

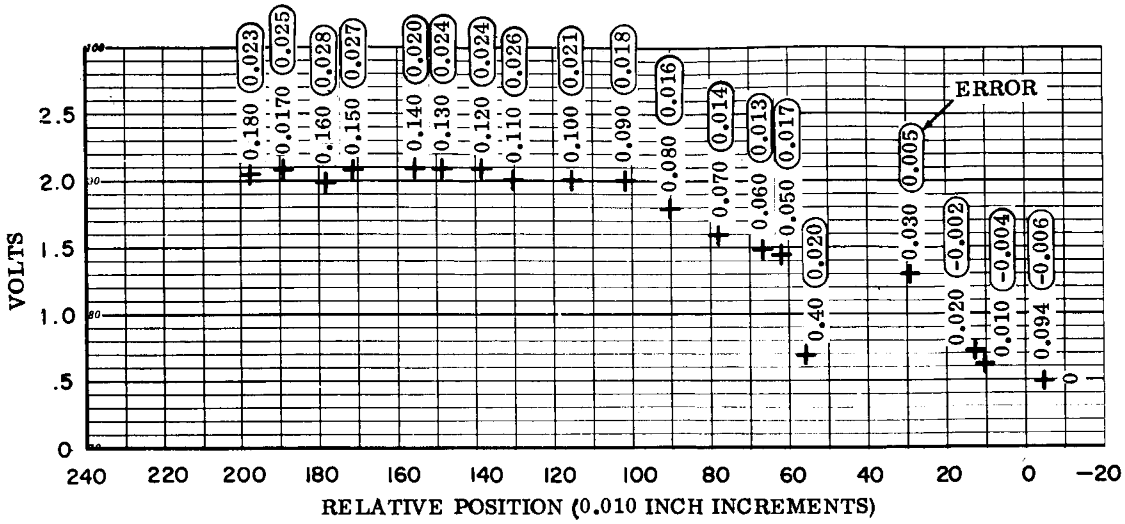


1 TO 3.8 SIGNAL RATIO AT REFLECTO-SCOPE
REBALANCED AT TEKTRONIX SCOPE AND INJECTING
HOLE SIGNAL INTO THE INVERTED SIGNAL CHANNEL.

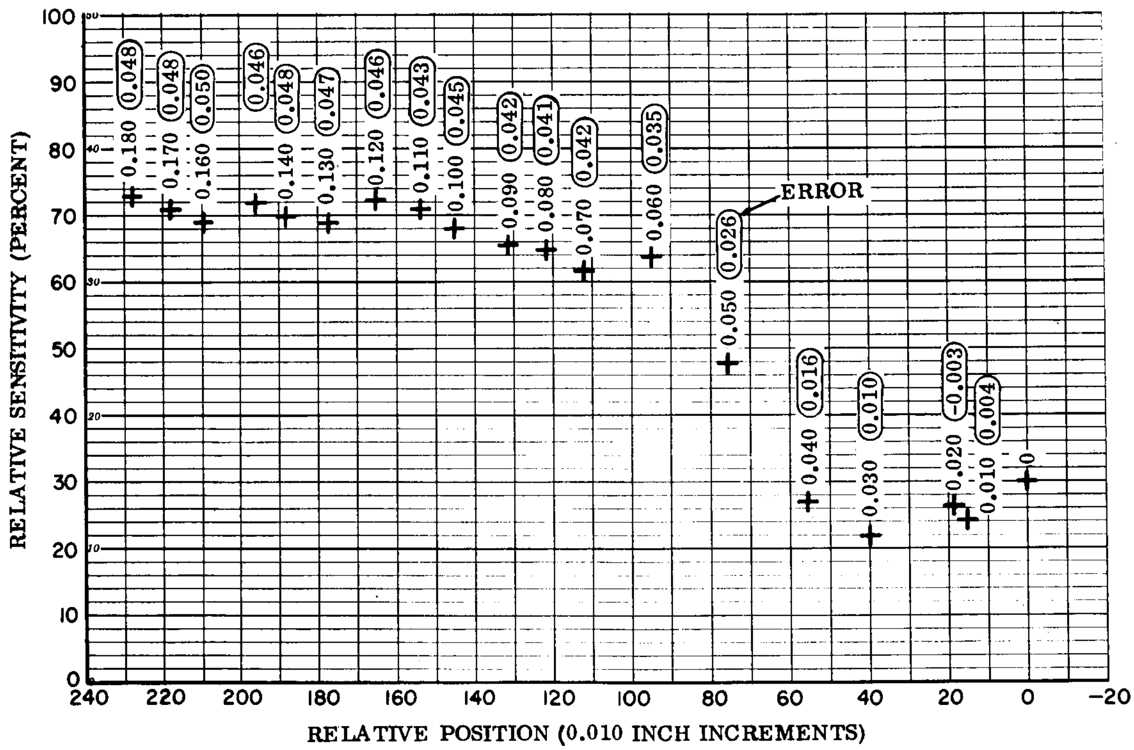


BALANCED SIGNAL AT ULTRASONIC REFLECTO-SCOPE

Figure 18. Comparison of Balanced Signals at Reflectoscope and Compensated Signal at Tektronix Scope (inverted channel)



3.3 TO 2.1 SIGNAL RATIO AT REFLECTO-SCOPE
REBALANCED AT TEKTRONIX SCOPE AND INJECTING
HOLE SIGNAL INTO THE NON-INVERTING SIGNAL CHANNEL.



BALANCED SIGNAL AT ULTRASONIC REFLECTO-SCOPE

Figure 19. Comparison of Balanced Signals at Reflectoscope and Compensated Signal at Tektronix Scope (noninverted channel)

When using the UM-721 ultrasonic equipment and changing position of the reject control to a minimum, the linearity changes in the first .100-inch as can be seen in Figure 20. Notice that the linearity is affected for both the compensated and noncompensated system and that it is even possible to get a negative direction indicated. After the first .070-inch on the ultrasonic scope the normal .050-inch error is indicated. Figure 21 shows the result of using some reject amplitude. As can be seen there is a more uniform progression of position than with no reject signal.

AUTOMATIC TRACKING OF SLOT

Automatic tracking of a machined slot has been accomplished and tracking of increments as small as .001 inch was found possible. The "Ultrasonic Fatigue Crack Detector" and servo motor system is shown in Figure 22.

As previously with the manual tracking, a slot was machined out away from the hole for approximately .180-inch. Then the equipment was tuned and positioned to produce the required balanced signals. The first test was started by cutting the slot using .001-inch increments and recording the automatic positioning for each cut out to .010-inch. Then the cutting rate was increased by machining the slot, still using .001-inch increments, but rapidly making one cut after another for a total of .005-inch. Then the new position was recorded and compared with the length of the machined slot. Different cutting rates were tried to determine the effects and response of the transducer system as would happen with different rates of crack propogation. This was continued out with a maximum error of +.003, -.006 for .100-inch (Figure 23). Hunting of the transducer took place after locating a portion of approximately .010-inch. This was a result of backlash in the system, e.g., a position would be indicated, a slight overrun would occur, the servo motor would reverse and go back .010-inch before there was an appreciable signal change on the ultrasonic video display. However, even with this hunting, the same points on either end of the hunting cycle would repeat each time.

This process of cutting a slot was continued for approximately a .500-inch. Some difficulties were encountered with the back reflector plate losing some coupling. This specimen was wider than any of the specimens previously used. But by readjusting the plate and maintaining the back reflection amplitude it was possible to follow the slot with an accuracy of +.010, -.005-inch.

A second test was conducted cutting a slot starting at .125 inch and cutting to a length of 1.000 inch (Figure 23). The test was run for 24 hours without any change. The maximum error range was ± .012-inch.

With further research the system can be improved to reduce the hunting of the transducer and to reduce the tolerance spread.

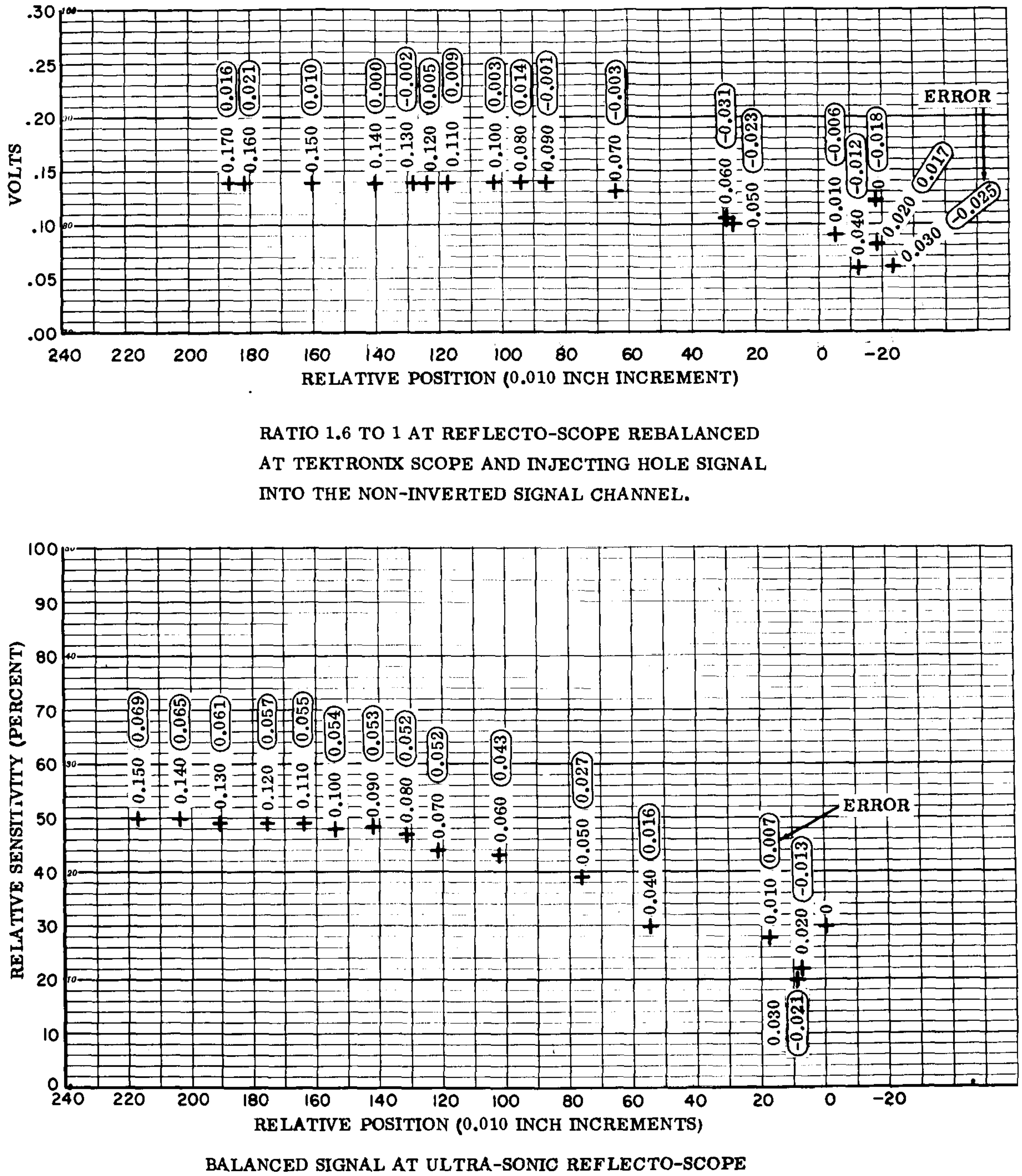


Figure 20. Comparison of Conditioned and Reflectoscope Balanced Signals with no Reject

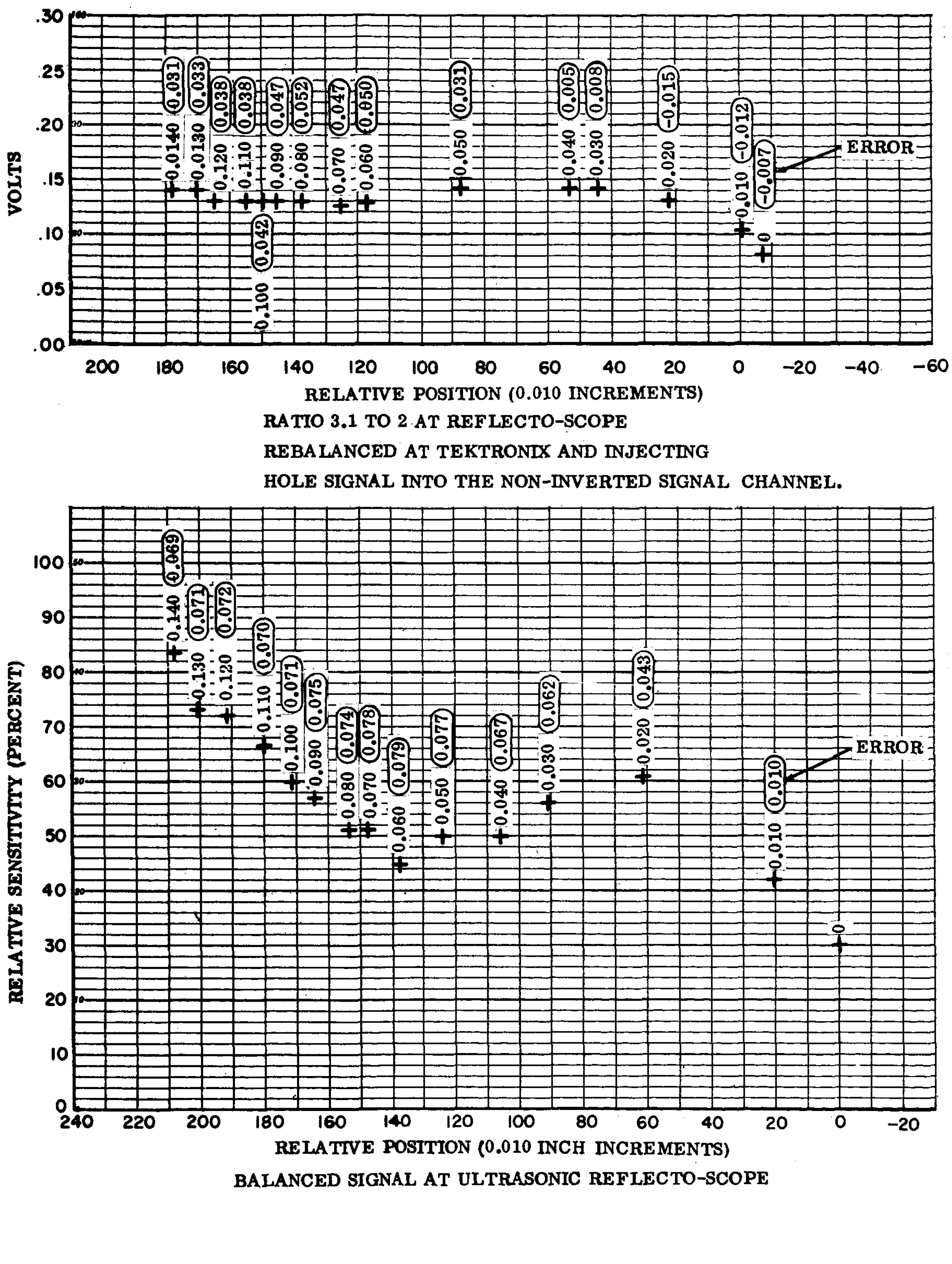


Figure 21. Comparison of Conditioned and Reflectoscope Balanced Signals with Reject

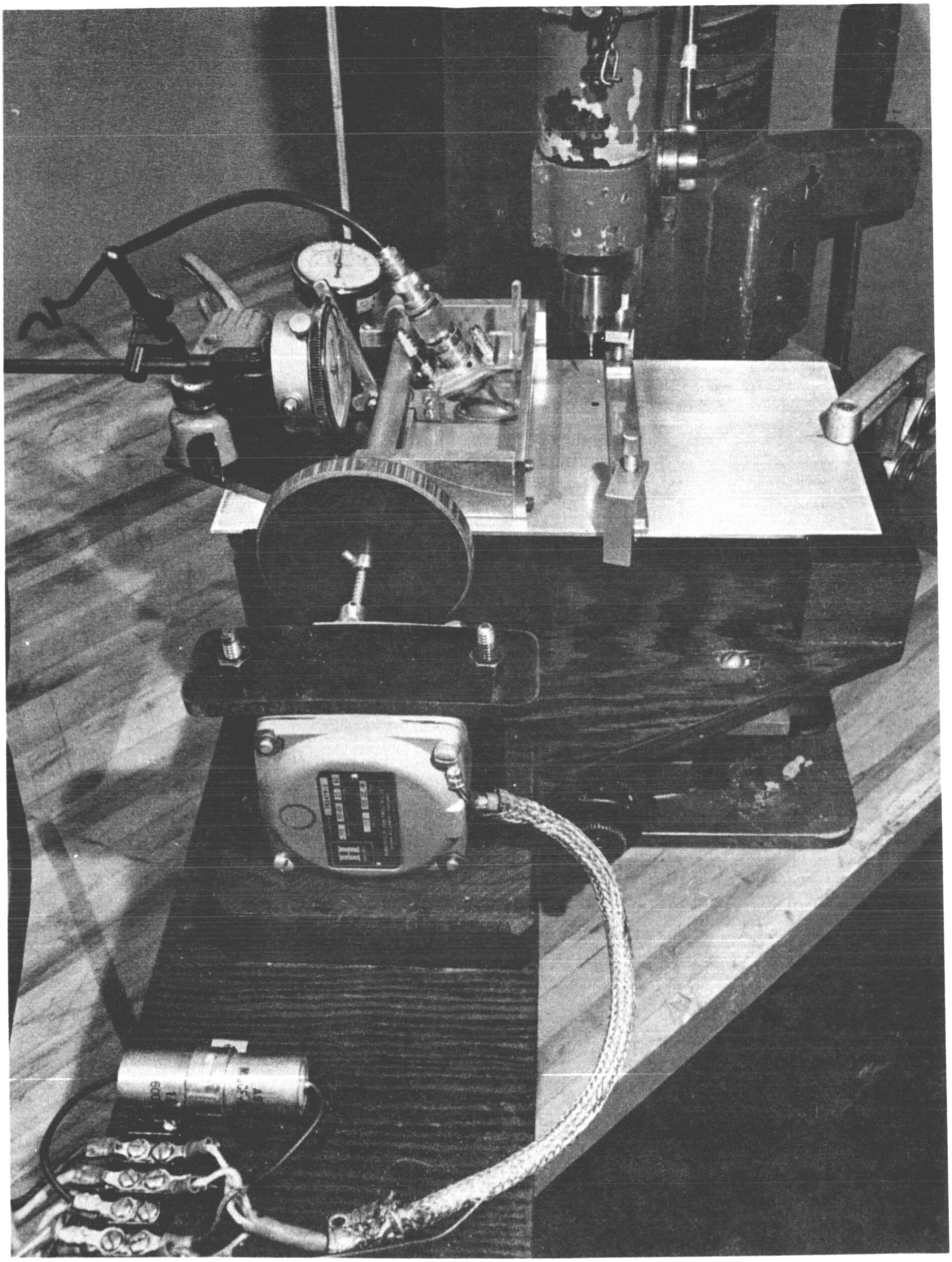


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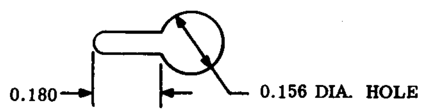
Figure 22. Close-Up View of Servo Driven Transducer System

TEST #1

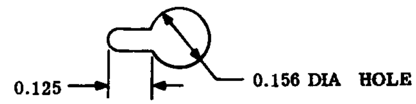
STARTING CONFIGURATION - 2024-T3 ALUM. ALLOY



SLOT LENGTH AFTER 0.180	TRANSDUCER POSITION	ERROR
0	0	0
0.001	0.002	0.001
0.002	0.003	0.001
0.003	0.004	0.001
0.004	0.0055	0.0015
0.005	0.006	0.001
0.006	0.0075	0.0015
0.007	0.0085	0.0015
0.008	0.0095	0.0015
0.009	0.010	0.001
0.010	0.010	0
Cut 0.005 machining 0.001 increments one after another.		
0.015	0.0125	-0.0025
0.020	0.015	-0.005
0.025	0.019	-0.006
0.030	0.025	-0.005
0.035	0.032	-0.003
0.040	0.041	0.001
0.045	0.0475	0.0025
0.050	0.051	0.001
0.055	0.056	0.001
0.060	0.062	0.002
0.065	0.065	0.000
0.070	0.070	0.000
0.075	0.075	0.000
0.080	0.080	0.000
0.085	0.0875	0.0025
0.090	0.093	0.003
0.095	0.0975	0.0025
0.100	0.103	0.003

TEST #2

STARTING CONFIGURATION - 2024-T3 ALUM. ALLOY



SLOT LENGTH STARTING AT 0.125	TRANSDUCER POSITION	ERROR
0.125	0.129	0.004
0.130	0.135	0.005
0.135	0.143	0.008
0.140	0.149	0.009
0.145	0.154	0.009
0.150	0.159	0.009
0.155	0.165	0.010
0.160	0.169	0.009
0.165	0.177	0.012
0.170	0.181	0.011
0.010 increments		
0.180	0.190	0.010
0.190	0.201	0.011
0.200	0.211	0.011
0.210	0.219	0.009
0.220	0.227	0.007
0.230	0.231	0.001
0.240	0.243	0.003
0.250	0.247	-0.003
0.260	0.258	-0.002
0.270	0.268	-0.002
0.280	0.276	-0.004
0.290	0.291	0.001
0.300	0.300	0.000
0.310	0.309	-0.001
0.320	0.319	-0.001
0.330	0.329	-0.001
0.340	0.343	0.003
0.350	0.352	0.002
0.360	0.362	0.002
0.370	0.369	-0.001
0.380	0.379	-0.001
0.390	0.389	-0.001
0.400	0.400	0.000
0.410	0.410	0.000
0.420	0.414	-0.006
0.430	0.419	-0.011
0.440	0.480	-0.010
0.450	0.441	-0.009
0.460	0.451	-0.009
Small air bubble in transducer housing (refilled.)		
0.470	0.463	-0.007
0.480	0.469	-0.011
0.490	0.480	-0.010
0.500	0.493	-0.007
0.510	0.503	-0.007
0.520	0.515	-0.005
0.530	0.520	-0.010

SLOT LENGTH STARTING AT 0.125	TRANSDUCER POSITION	ERROR
0.540	0.529	-0.011
0.550	0.541	-0.009
0.560	0.553	-0.007
0.570	0.564	-0.006
0.580	0.570	-0.010
0.590	0.580	-0.010
0.600	0.590	-0.010
0.610	0.600	-0.010
0.620	0.610	-0.010
0.630	0.619	-0.011
0.640	0.628	-0.012
Restarted from the day before		
0.650	0.640	-0.010
0.660	0.651	-0.009
0.670	0.664	-0.006
0.680	0.672	-0.008
0.690	0.683	-0.007
0.700	0.692	-0.008
0.710	0.702	-0.008
0.720	0.713	-0.007
0.730	0.725	-0.005
0.740	0.735	-0.005
0.750	0.744	-0.006
0.760	0.756	-0.004
0.770	0.766	-0.004
0.780	0.778	-0.002
0.790	0.787	-0.003
0.800	0.796	-0.004
0.810	0.306	-0.004
0.820	0.821	0.001
0.830	0.830	0.000
0.840	0.840	0.000
0.850	0.849	-0.001
0.860	0.858	-0.002
0.870	0.871	0.001
0.880	0.876	-0.004
0.890	0.886	-0.004
0.900	0.893	-0.007
0.910	0.904	-0.006
0.920	0.926	-0.004
0.930	0.924	-0.006
0.940	0.932	-0.008
0.950	0.941	-0.009
0.960	0.954	-0.006
0.970	0.965	-0.005
0.980	0.977	-0.003
0.990	0.982	-0.008
0.1000	0.991	-0.009

Figure 23. Comparison of Length of Slot with Automatic Tracking Transducer Indicated Location

THE ELECTRICAL SYSTEM

The equipment required for the electrical-system (Figure 24) was not commerically available; this made it necessary to assemble filters, delay line, dual gates, and a signal conditioning unit. In the early experimental setup low amplitude reflected signals were found troublesome in effecting a balanced signal display. A two channel signal conditioning unit was constructed to control output signal amplitude, it was used mainly with the Sperry Ultrasonic Reflectoscope type UM-721.

In the early part of the work, considerable drift was observed in viewing the signals on an oscilloscope. Base line drift in the oscilloscope was the main trouble, which stabilized after several hours of use. This was overcome by leaving the equipment energized overnight, only shutting down on weekends. Also of major importance is the 60 cycle supply system. It was necessary to install a regulated ac isolated supply to all the system components to eliminate line noise and variation of signal amplitude.

The electronic components of the system operate to extract two signal portions from the video display of an ultrasonic reflectoscope, and use these signals to automatically control the transverse position of an ultrasonic transmitter-receiver unit (transducer) across the face of a fatigue specimen (Figure 24). The complete video signal is taken from the external output terminal of the ultrasonic unit and applied to the input of the dual gate unit. The gates triggered by a pulse from the ultrasonic unit allow signals in the time gated zone to pass through for further conditioning. The lead signal, from the crack or starting notch is then fed through an adjustable delay line where the signal is brought into step (time agreement) with the second signal. The two signals which are now in phase are brought to the dual channel signal conditioning unit. The first channel compensates for the attenuation in the delay line and the second inverts the undelayed signal. The amplitude difference between the two voltages is then applied to the servo amplifier to control the motor. A cross connected control of gain was used in only one group of tests (the scheme is shown in Figure 27B), and resulted in accentuating the voltage excursions by having the lower level signal (#2) increase the gain of the higher signal (#1) as the crack progresses. The individual units are described in the next paragraphs.

TRIGGER

Conventional interconnections between components were used, namely, RG174U shielded cables and BNC connectors. The video signal to the gate was taken from pin 19 of the 24 pin, keyed barrier connector on the rear panel of the Sperry UM-721. The trigger signal (isolated with 5000 OHM series resistor) to start the gate action was taken from pin 10. It can be initiated from the main ultrasonic pulse or the first echo signal. In the tests conducted in this study the trigger was initiated by the main

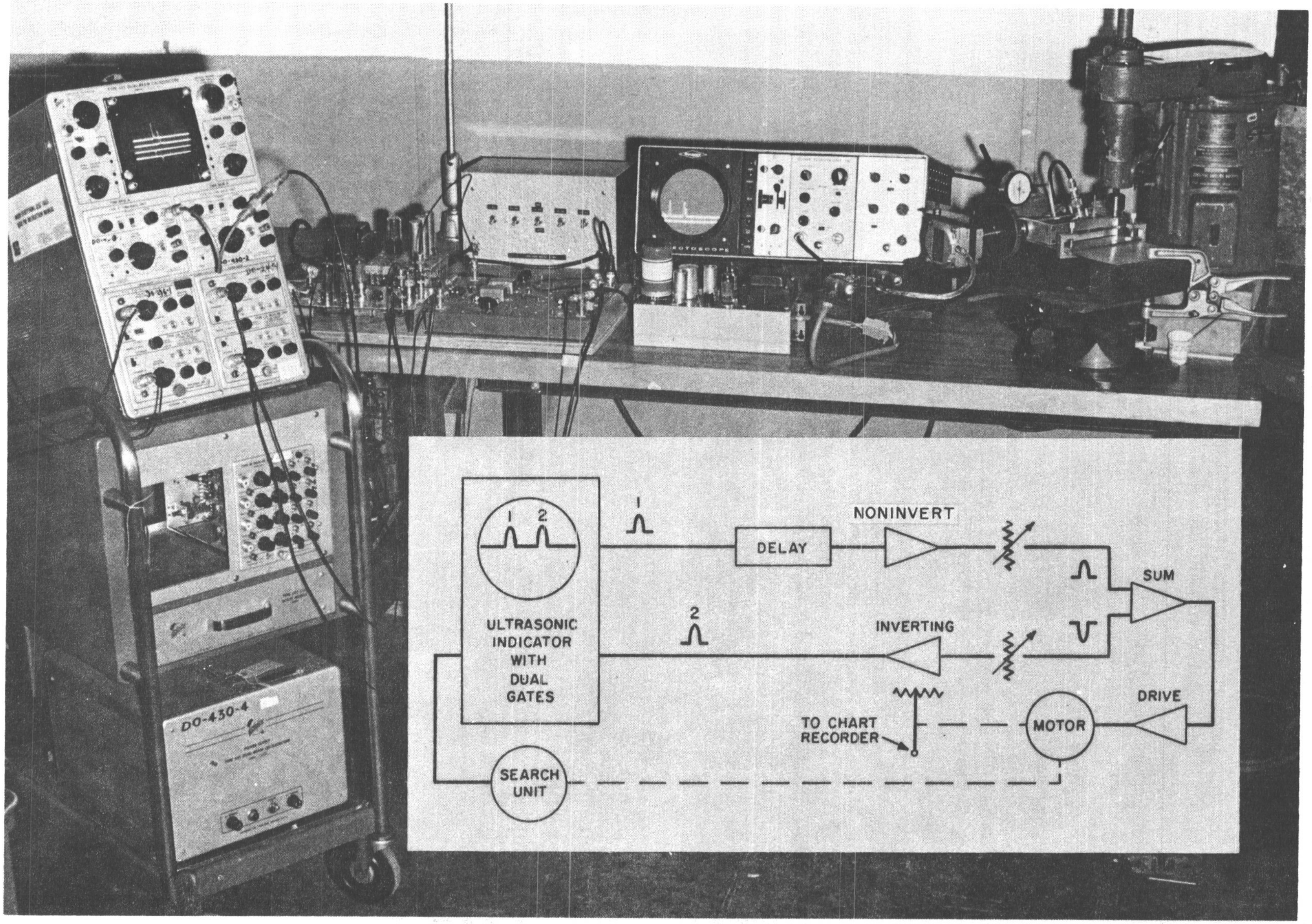


Figure 24. Overall View of Test Setup for Automatic Tracking of Slot

MR-4901-6

pulse and adjusted for 13 volts and 15μ sec duration. Operating at this level gave a very reliable trigger and stable scope display of amplifier outputs. The oscilloscope was a "Tektronix" model 555 dual beam unit with two type CA dual trace preamplifiers that provided for simultaneous viewing of four signal traces. The oscilloscope sweep (20 μsec cm) is also initiated by the trigger.

DUAL GATE

The two gate systems are identical and are used to establish a zone or time band necessary to display the signals of interest and eliminate all other extraneous signals including noise. The individual gates (rectangular wave) are initiated by the trigger from the ultrasonic unit and adjusted to start 15 μsec to 15 msec delay after a trigger pulse and in time duration (20 μsec to 20 msec). In operation, the gate start and duration controls are adjusted to turn off the shunt path (local series diode circuit) for the selected interval across the input video signal, allowing signal transmission to the output terminal. The dual time gated amplifier is shown in Figures 25A and 25B. Only one section of the dual gate is shown in the wiring diagram since they are identical in layout and constrcution. The wave forms and values shown are observed when operating with the Sperry Ultrasonic Comparator #56A001.

DELAY LINE

The selective delay line is a lumped parameter type series inductor, shunt capacitor. Comparison of the input and output traces (Figure 26) of the composite curves show adequate fidelity. The upper trace is an actual reflection (5 volt) signal (from discontinuity) input to the delay line. The lower composite trace is the output at 0, 15, 35, 55, 75, 95 and 115 microseconds switch settings. Intermediate delays are omitted for clarity. Signal losses are equalized for each selector switch by insertion of equalizing attenuators at each switch. Figure 26 is a simplified wiring diagram of the variable step delay line. All sections are identical with the exception of the input and output. The attenuators are laboratory adjusted for loading and loss equalization at each selector switch.

SIGNAL CONDITIONING UNIT

Tests results, using the Ultrasonic Reflectoscope UM721 indicated that crack location accuracy could be improved by compensating for signal variations. The two channel amplifier was modified by adding a cross connected stage to vary the gain (Figure 27A). Additional accuracy was obtained over a fixed ratio between the two signals. However, the cross connection was removed because further work is necessary to follow up this correction technique. The balance of the work has performed with the amplifier, as illustrated in Figure 27B, without the cross connection.

Drive Motor and Control

The drive motor for the transverse control (1.1 in. per. min.) of the transducer is a 115 volt 60 cycle, two phase Honeywell unit of 105-oz. inch

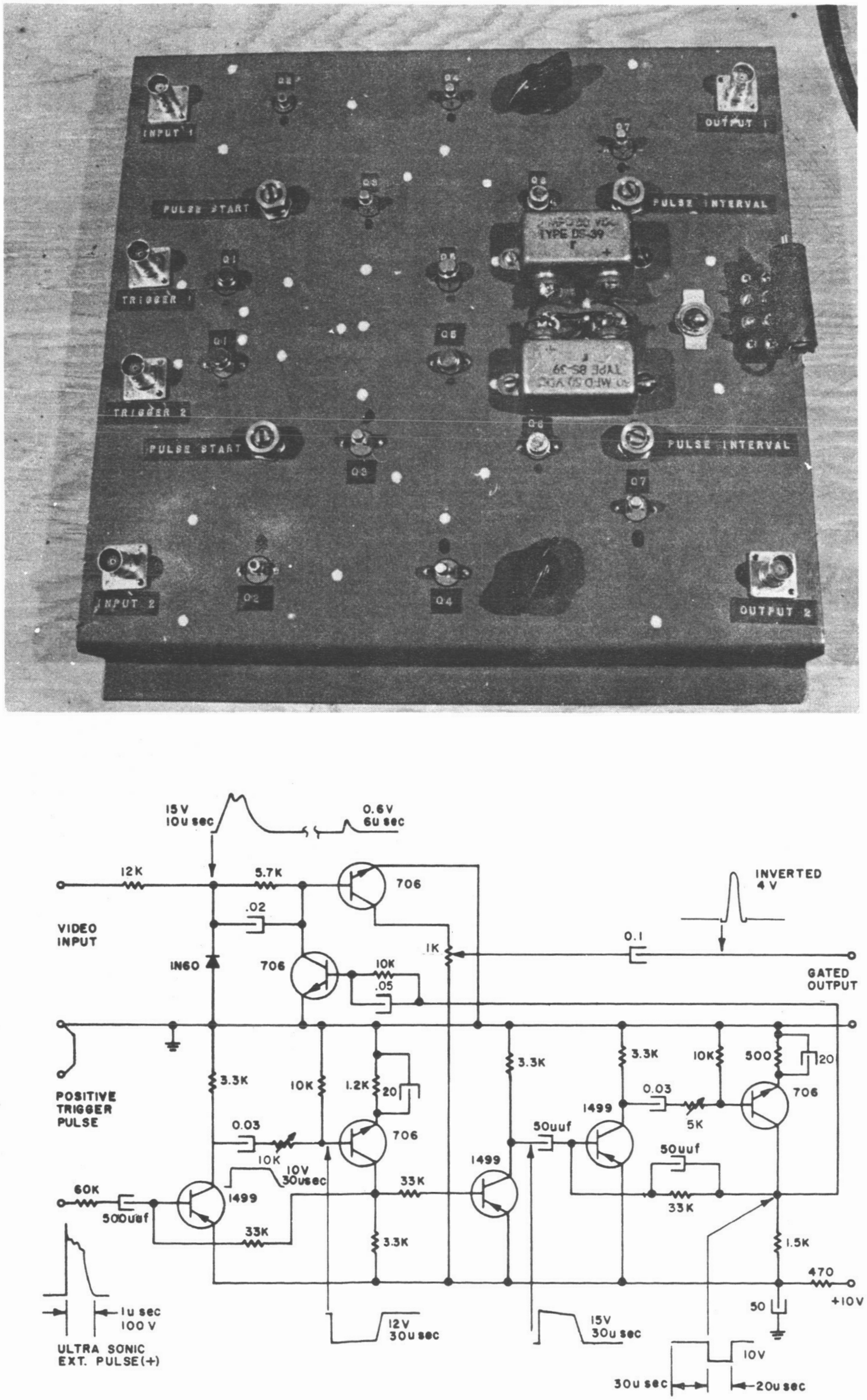
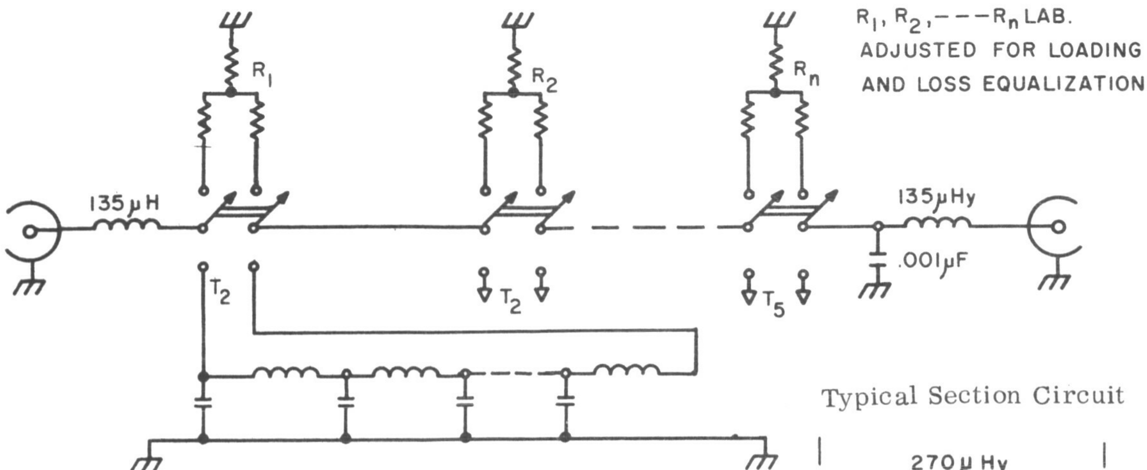
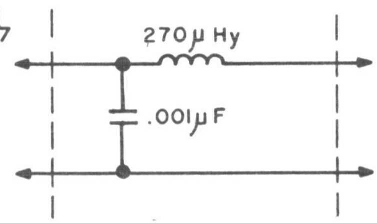


Figure 25. Dual Gate Unit

Simplified Diagram Delay Line



Typical Section Circuit



Delay Time and Respective Number of Sections

	T1 =	5 microseconds	10 Sections
	T_1 =	5 microseconds	10 Sections
	T_2 =	10 microseconds	20 Sections
	T_3 =	10 microseconds	20 Sections
	T_4 =	30 microseconds	60 Sections
	T_5 =	60 microseconds	120 Sections
Total		115 microseconds	230 Sections

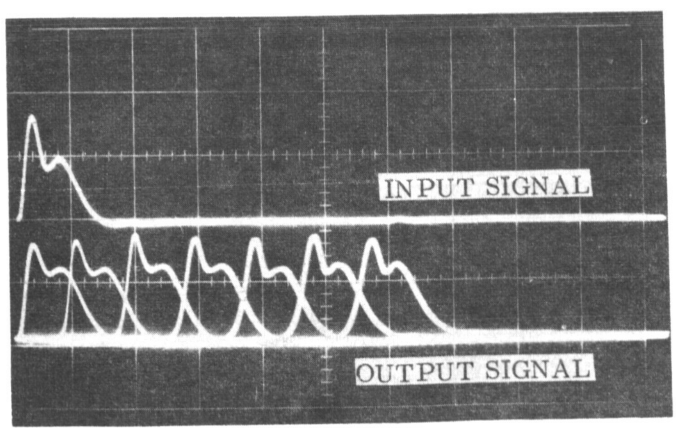
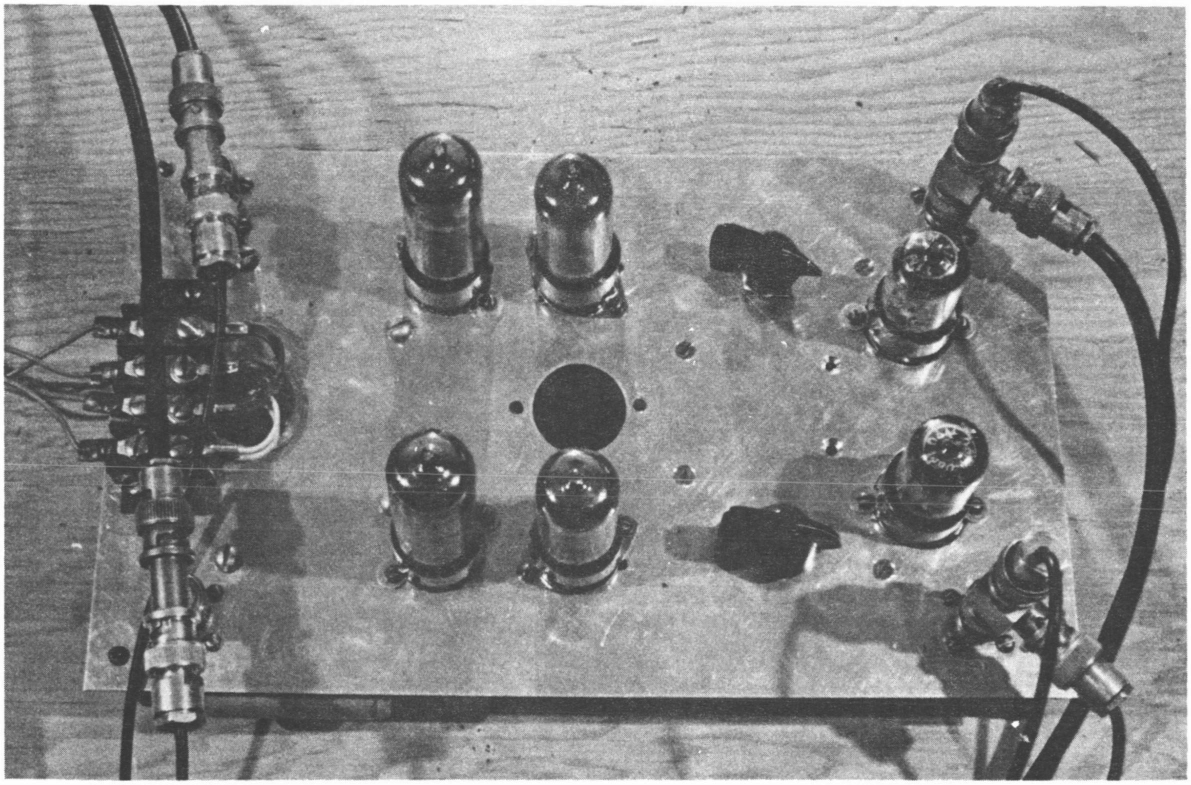


Figure 26. Step Delay Line



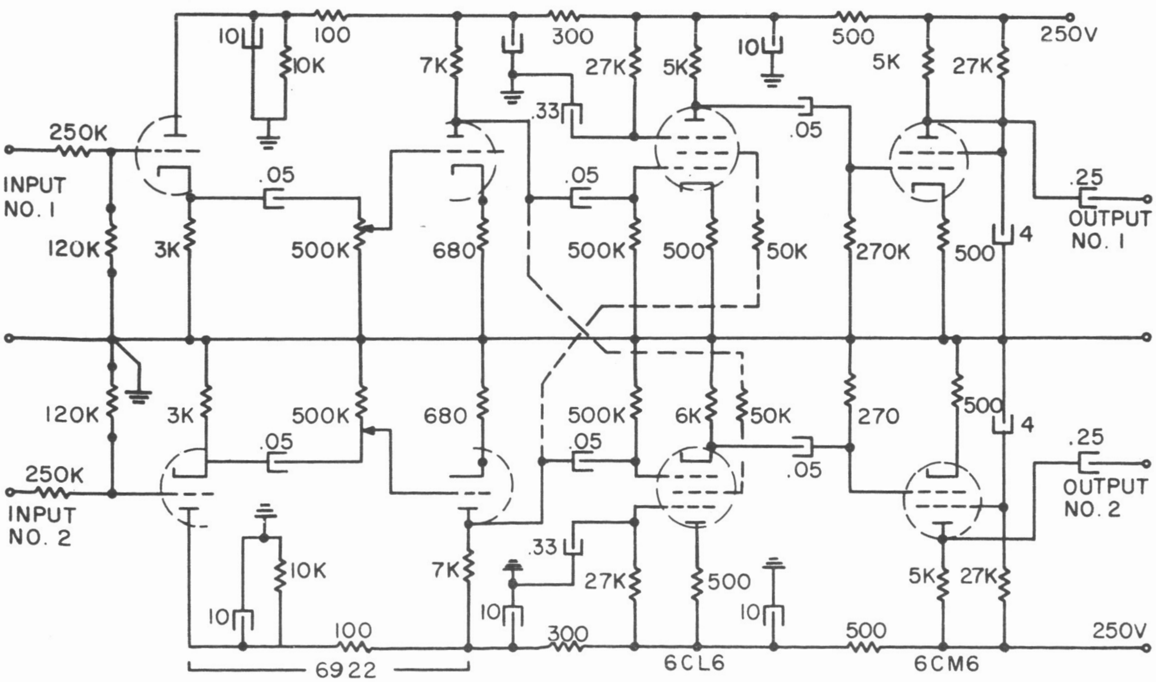


Figure 27. Two Channel Signal Conditioning Unit

stall torque and maximum of 23 rpm. The motor has a flexible shaft coupling to a 7/16" - 20 lead screw of the transducer assembly. Control of motor operation (cw - ccw) is obtained from the relative polarity of the input signal to the chopper stage of the drive motor amplifier. The control amplifier is shown in Figure 28.

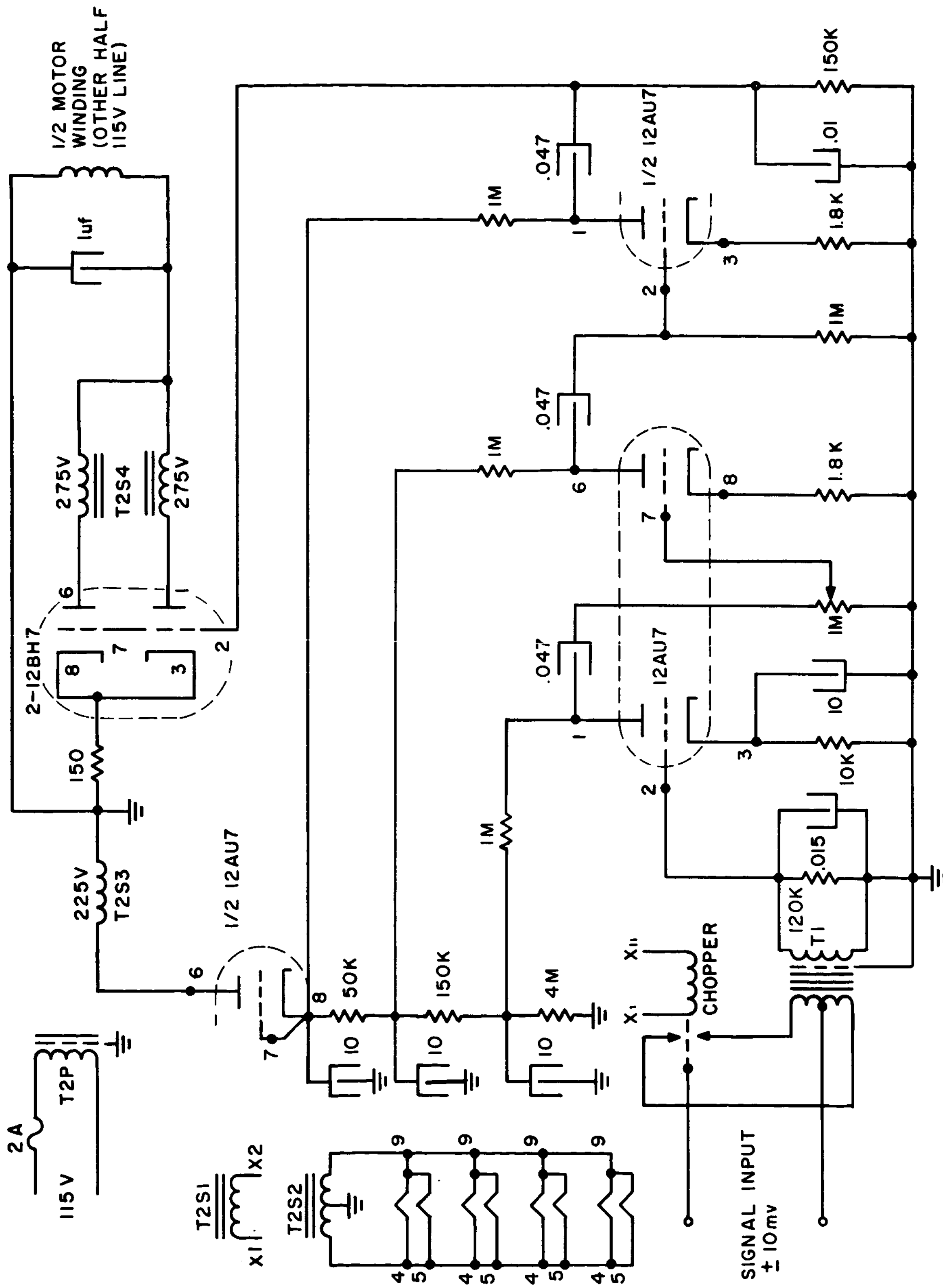


Figure 28. Servo Amplifier

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APPENDIX

ULTRA-SONIC FATIGUE CRACK DETECTOR

DET.	QTY.	DIA.	THICK	WIDTH	LENGTH	MATERIAL	REMARKS	S	Z
28	2				1/2	5-40 R.H.M. SCR.		1	5E
27	2					#8-32 NC HEX NUT	COMML	1	5A
26	2				1 1/4	#8-32 NC SOC HD.	ALLEN CAP SCREW	1	6A
25	1					PARCO O-RING #PRP-020	PLASTIC & RUBBER PROD.	1	10D
24	1					PARCO O-RING #PRP-016	PLASTIC & RUBBER PROD.	1	10E
23	1				1/4	#6-32 NC SET SCREW	ALLEN	1	19F
22	1		3/4	1 1/4	1 3/4	ALUM.	TRANSDUCER SUPPT	1	19F
21	1		.250	4	7	ST. STL.	LOWER PLATE	1	13D
20	1		.250	4	7	ST. STL.	UPPER PLATE	1	13D
19	1					CL-1-KHS CARR-LANE	KNURLED HD. SCR.	1	7B
18	1				5/16	#6-32 NC - STL.	SET SCR.-ALLEN	1	5C
17	4				5/16	#4-40NC - BRASS	FILLISTER HD SCR.	1	5C
16	1		1	1 1/2	2	BRASS	FITTING	1	12A
15	1	1/4			1 1/2	PLEXIGLASS ROD		1	10B
14	1		1 3/4	1 1/2	2 1/2	PLEXIGLASS BLOCK	CARRIAGE BLOCK	1	10A
13	1					TEFLON COATED O-RING	TO SUIT	1	13B
12	1				1/4	#8-32 NC SET SCR.	ALLEN	1	9C
11	4				5/16	#6-32 NC-SOC. HD.	ALLEN CAP SCREW	1	8B
10	2				3/4	#6-32 NC-SOC. HD.	ALLEN CAP SCREW	1	4D
9	2				5/8	#6-32 NC-SOC. HD.	ALLEN CAP SCREW	1	4B
8	2					FAFNIR-#ABEC-MF4DD	FLANGED BEARING	1	5B
7	4					1/4 STL. FLAT WASHER	COMML.	1	5B
6	4					1/4-28 NF HEX NUT	COMML.	1	5B
5	1	.50			9 1/2	DR. ROD	SHAFT	1	15C
4	1	1 1/2				ALUM. ROD 6061-T651	FLANGE-([illegible]	1	6E
3	1	1 1/2			9	ALUM. ROD 6061-T651	TUBE	1	8D
2	1		.375	2	6 1/2	ALUM. TOOL'G PL 921-TDC	CROSS TIE PLATE	1	8C
1	2		.31	1 1/2	4	ALUM. TOOL'G PL 921-TDC	END PLATES	1	6A

SIZE

DO NOT SCALE DRAWING

TOOL NO. MRP 2667

SHEET 1 OF 1 — T.D. REV. ~

DRAWN	CHECKED	APPR'D	APPR'D	APPR'D	TOLERANCES	SCALE
J. MAZZOLA 12-1-66	[illegible] 1-20-67	[illegible] 1-20-67	[illegible]	[illegible]	DECIMAL 1PL. ± .1 | 2PL ± .03 | 3PL ± .010 | ANGULAR ± 0°30' (UNLESS OTHERWISE NOTED)	FULL SIZE

ULTRA-SONIC FATIGUE CRACK DETECTOR

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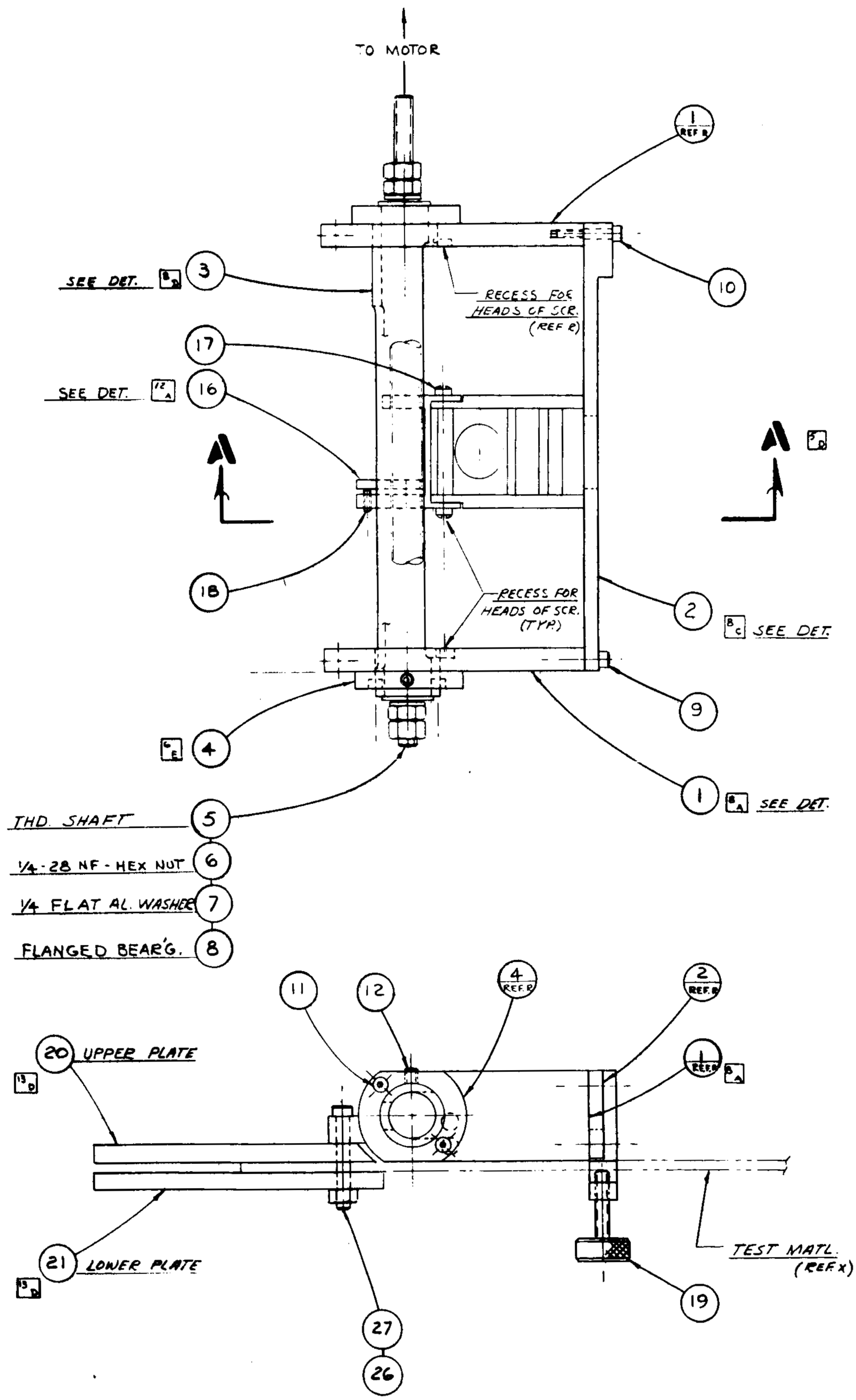
TOOL NO MRP 2667

Ultrasonic Fatigue Crack Detector (Dwg. No. MRP 2667)

(Sheet 1 of 9)



Ultrasonic Fatigue Crack Detector (Dwg. No. MRP 2667)

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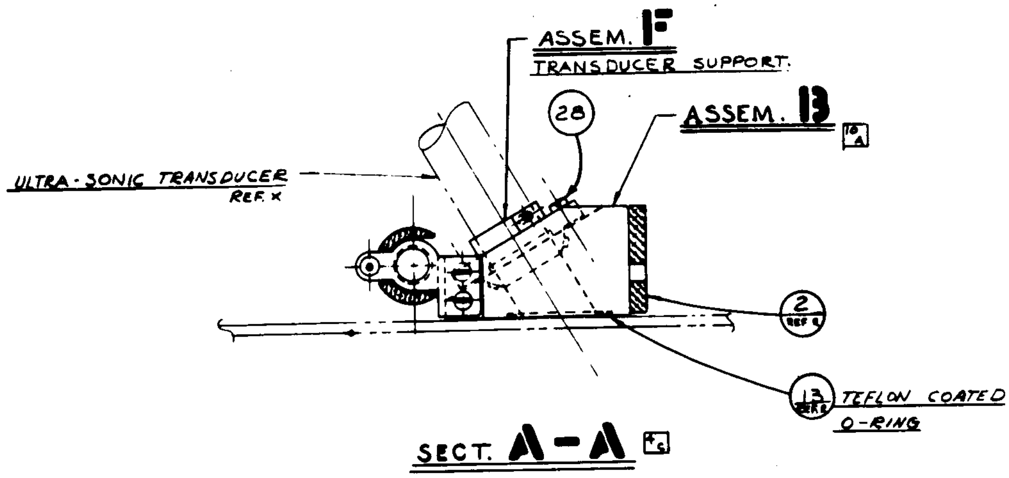
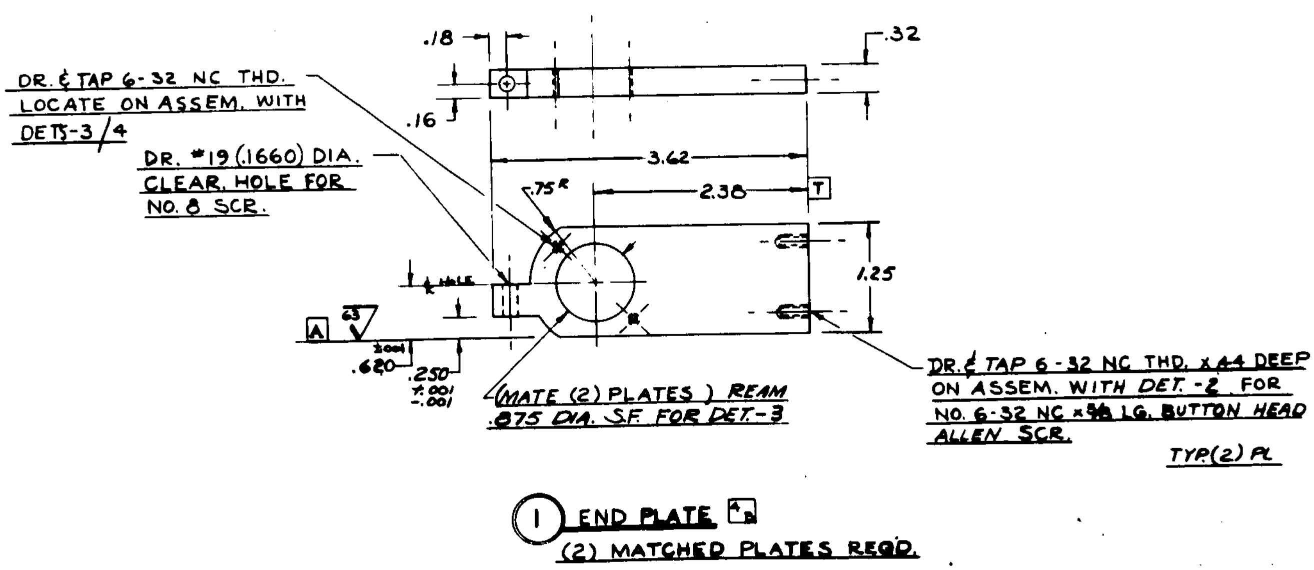
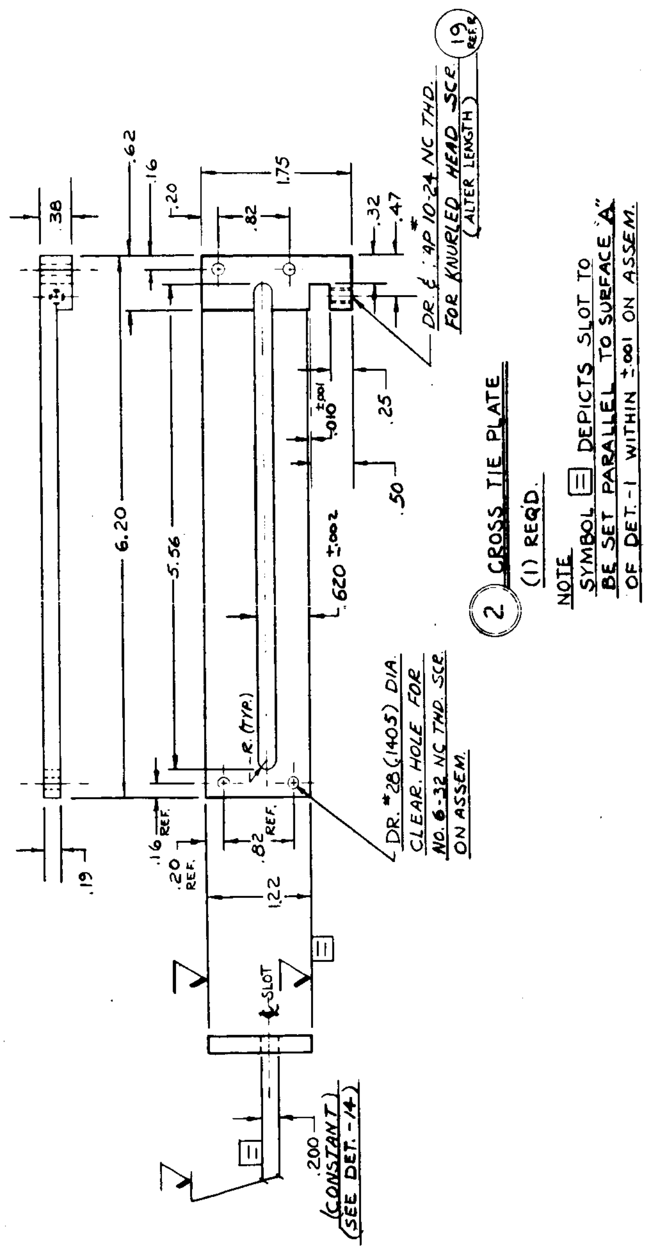




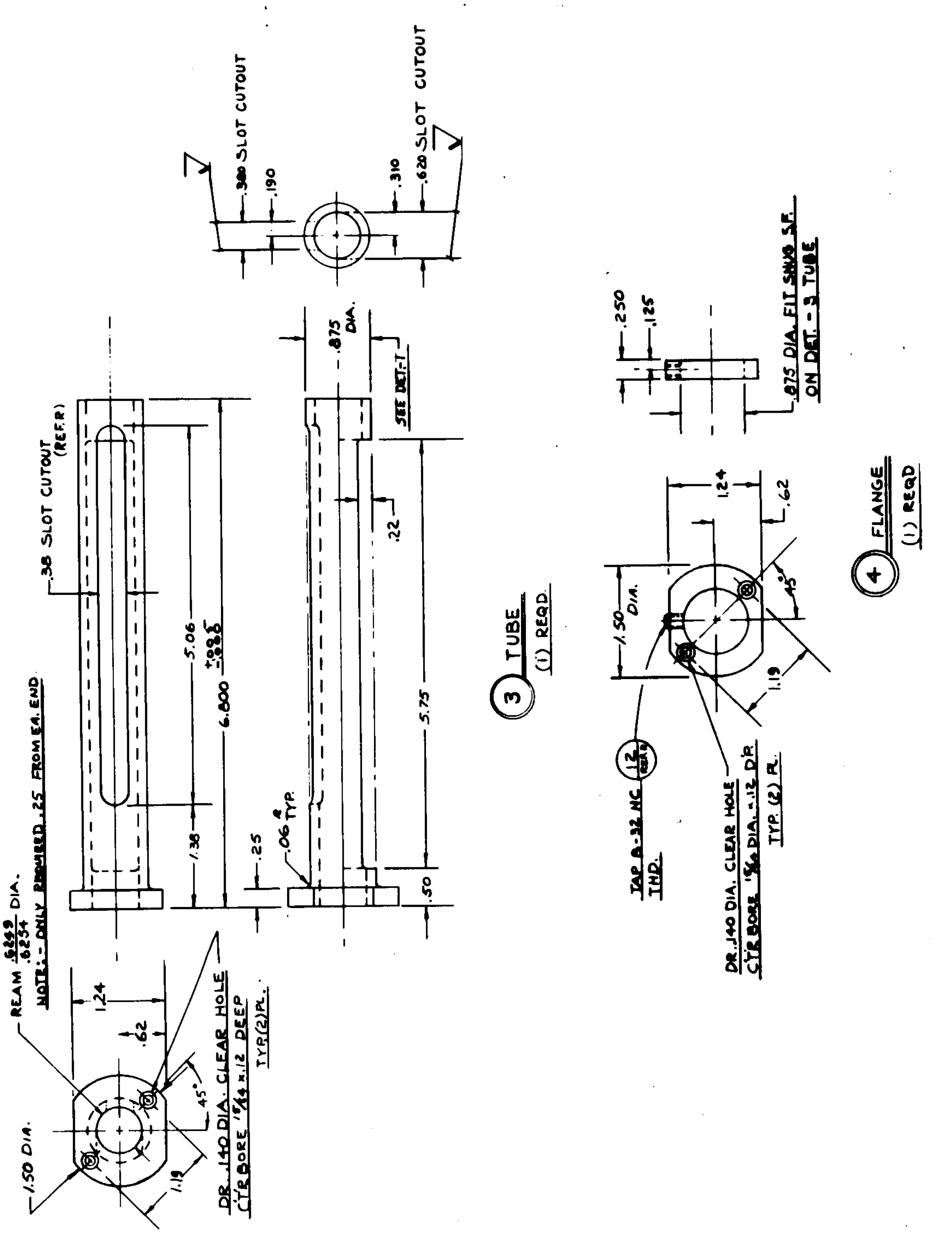
Ultrasonic Fatigue Crack Detector (Dwg. No. MRP 2667)

(Sheet 3 of 9)



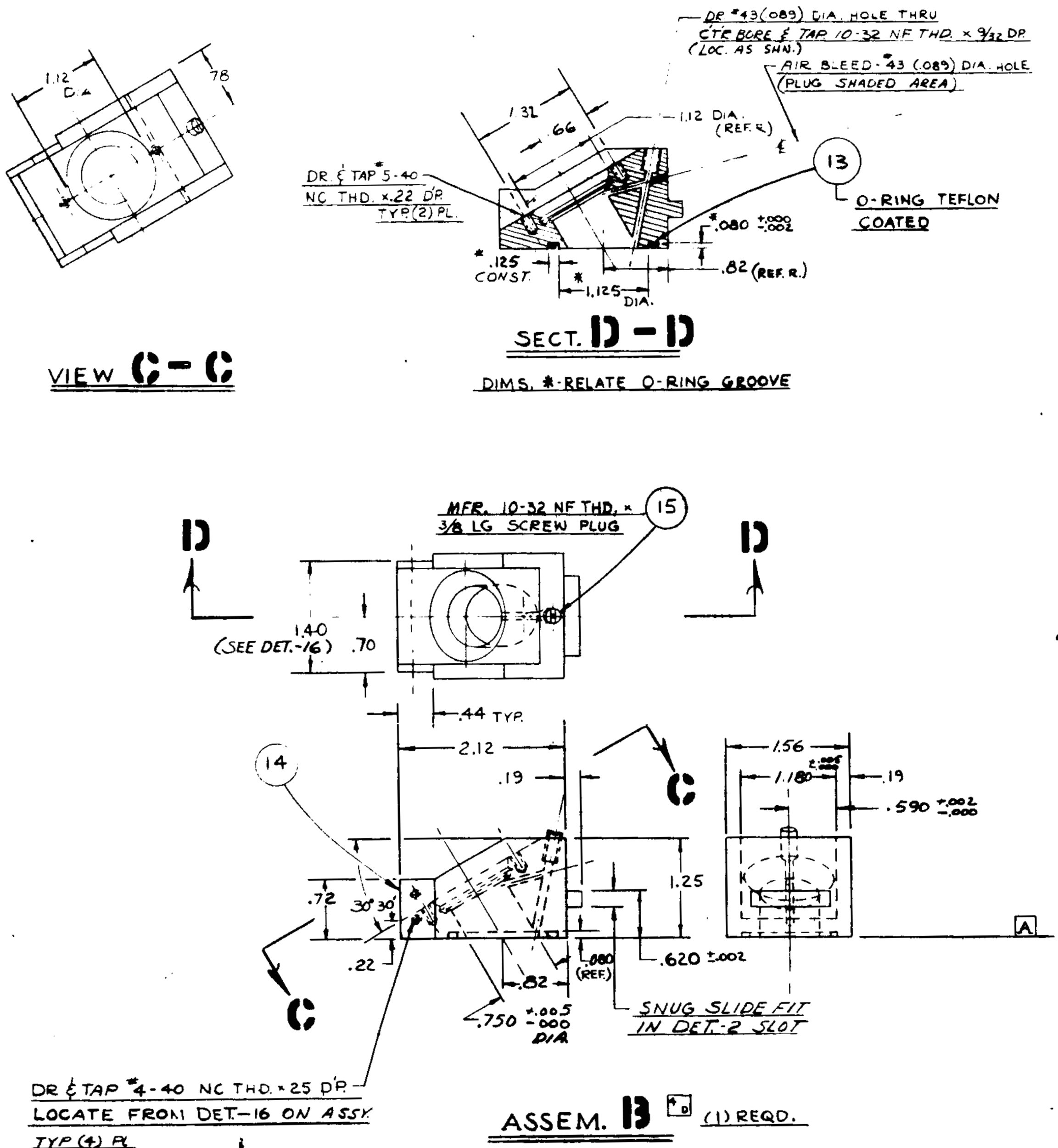
Ultrasonic Fatigue Crack Detector (Dwg. No. MRP 2667)

(Sheet 4 of 9)



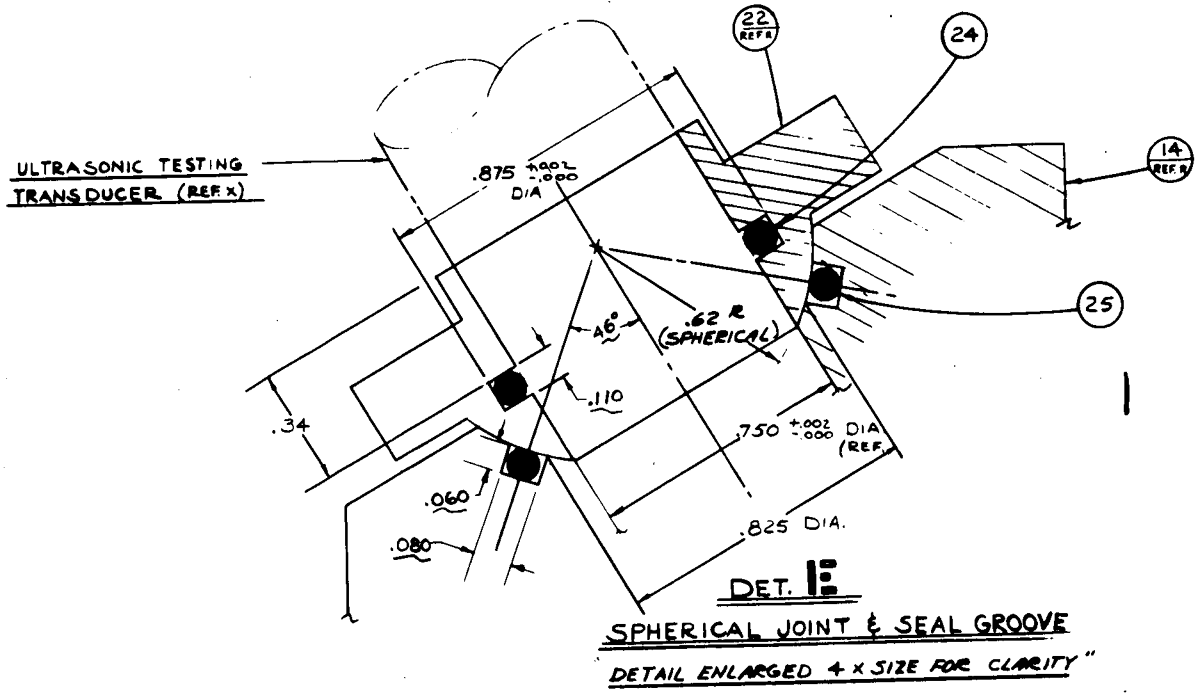
Ultrasonic Fatigue Crack Detector (Dwg. No. MRP 2667)

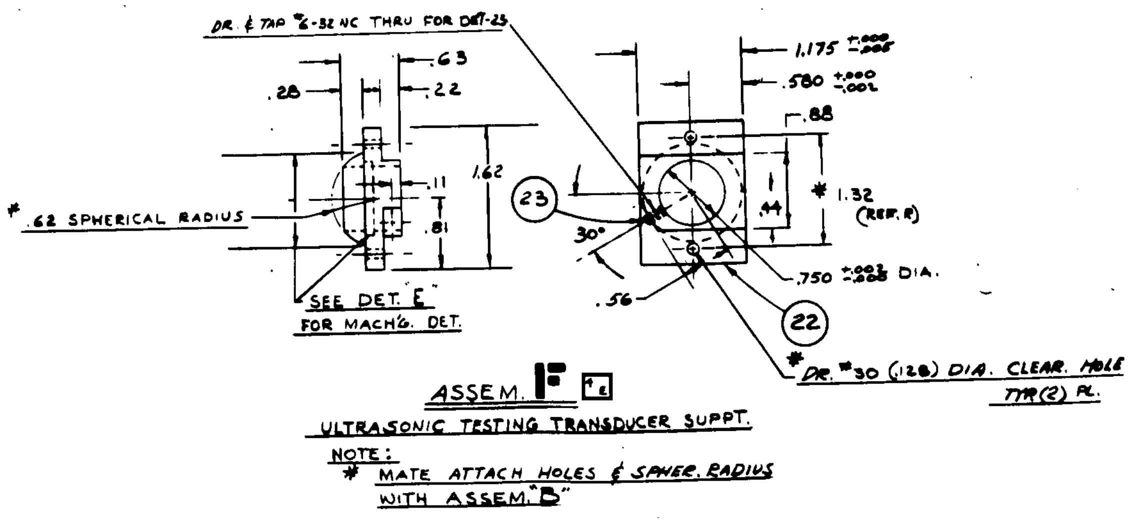
(Sheet 5 of 9)



Ultrasonic Fatigue Crack Detector (Dwg. No. MRP 2667)

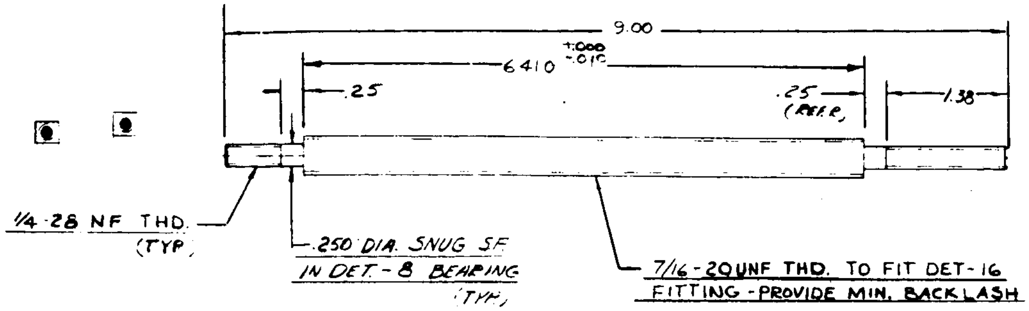
(Sheet 6 of 9)



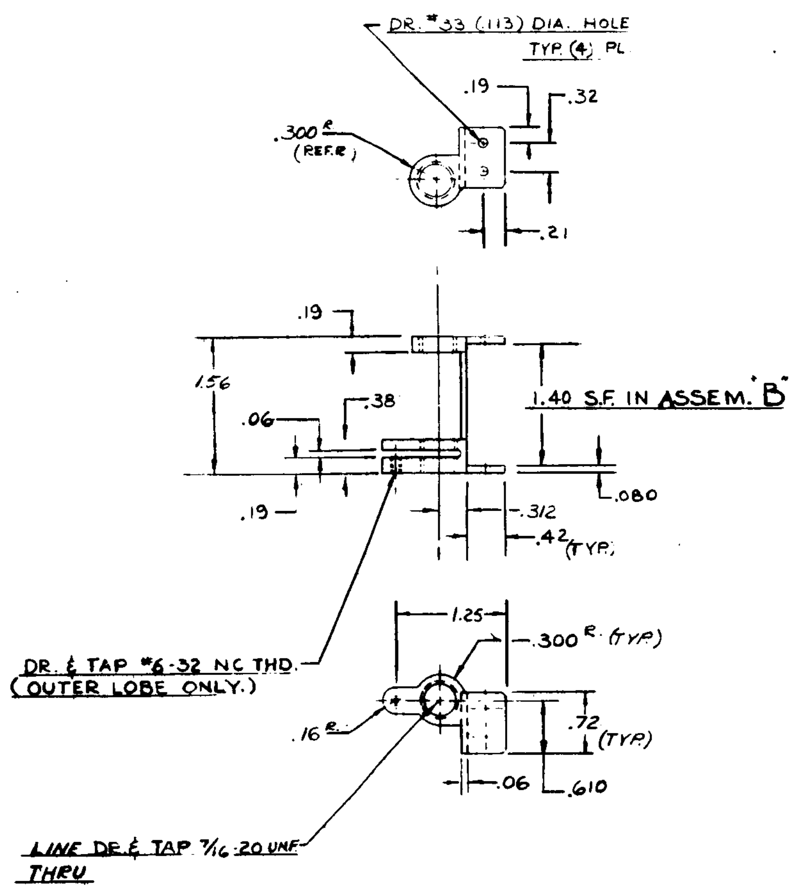


Ultrasonic Fatigue Crack Detector (Dwg. No. MRP 2667)

(Sheet 7 of 9)



5 THREADED SHAFT
(1) REQD.
CENTERS PERMITTED

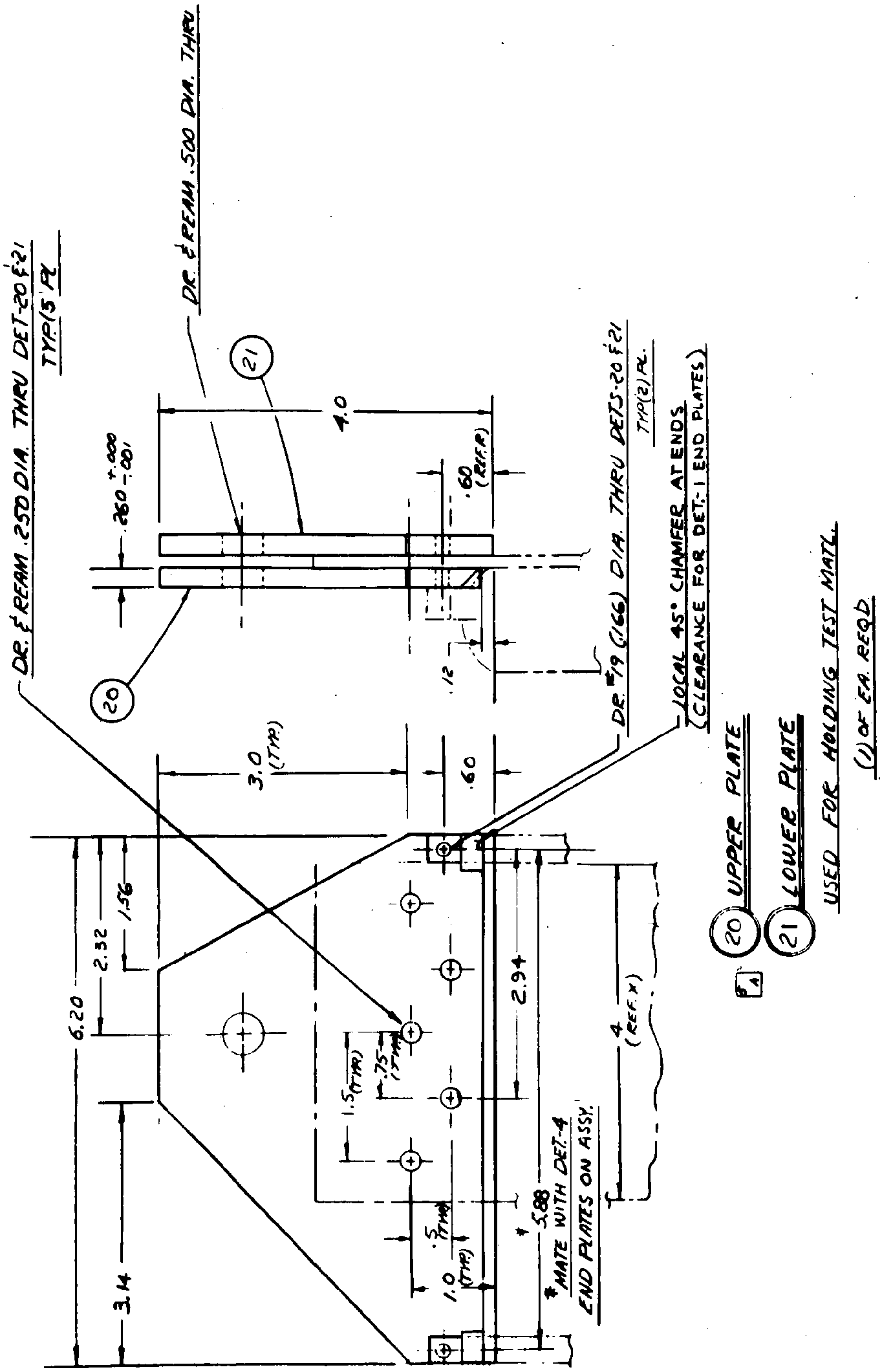


16 FITTING
(1) REQD

MANUFACTURE PROCEDURE:
DRILL & TAP 7/16-20 UNF HOLE FIRST & THEN MAKE MANDREL & MACH. ALL SURFACES REFERENCED TO THE ℄ HOLE

Ultrasonic Fatigue Crack Detector (Dwg. No. MRP 2667)

(Sheet 8 of 9)



Ultrasonic Fatigue Crack Detector (Dwg. No. MRP 2667)

(Sheet 9 of 9)

NASA CR 66320
National Aeronautics and Space Administration
DEVELOPMENT OF NONDESTRUCTIVE,
AUTOMATIC TECHNIQUE FOR THE MONITORING
AND RECORDING OF FATIGUE CRACK GROWTH.
Frank J. Hoppe and Nelson Inman
Fairchild Hiller - Republic Aviation Division.
pp
(NASA CONTRACTUAL REPORT)

Final report on the development of a single tracking probe producing a surface wave for the detection of a fatigue crack. A water coupled angle-transducer system was developed and traversed by a servo to follow the leading edge of a slot or a crack. Basic information on construction of the mechanical and electrical system is given. Operational tuning procedures, etc., are also detailed.

I. Hoppe, Frank J. and
Inman, Nelson.
Fairchild Hiller -
Republic Aviation Division
II. NASA-CR 66320