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REPORT M68-28-1

DEVELOPMENT OF A PULSE MODULATED ULTRASONIC IMAGING SYSTEM

Part I: General Description

by

HENRY B. KARPLUS

IIT Research Institute
Illinois Institute of Technology
Chicago, Ill. 60616

Final Report
Contract DA-36-038-AMC-2813(A)

May 1968

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DEPARTMENT OF THE ARMY
FRANKFORD ARSENAL
Philadelphia, Pa. 19137

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IITRI Project No. J6079
(formerly M6127)

AMCMS Code 5025.11.29901
DA Project 1T024401A34901

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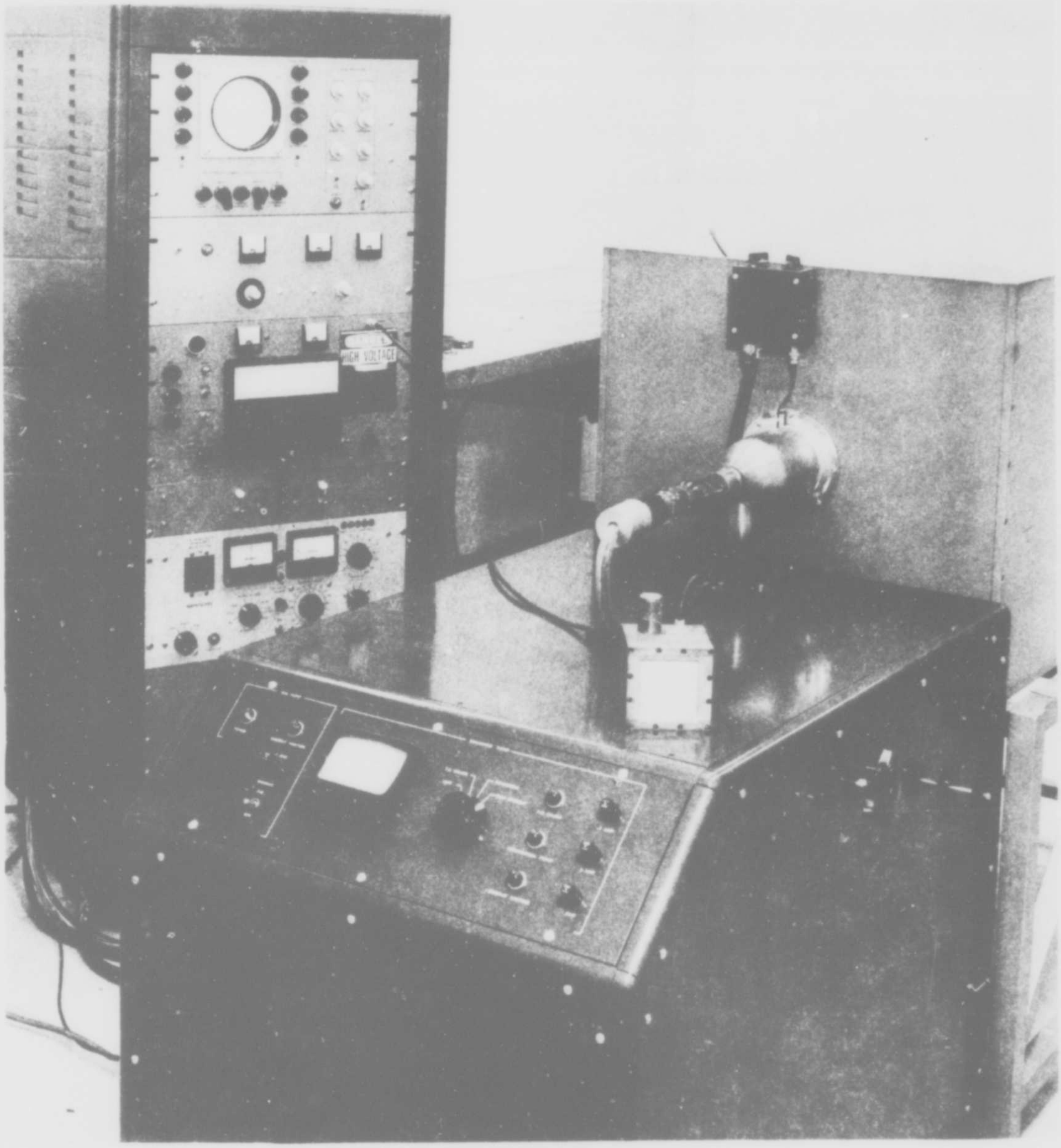
Fire Control Development & Engineering Laboratories
FRANKFORD ARSENAL
Philadelphia, Pa. 19137

May 1968



PULSED ULTRASONIC IMAGE CONVERTER

The converter tube is seen mounted on the pump unit in the foreground and the tank behind. The electronic control unit is on the left.

ABSTRACT

The development of an experimental, pulse modulated, ultrasonic imaging system is described. Details of the image tube and transducer plus a general account of the instrumentation are given.

The system was designed to have a wide range of resettable pulse repetition rates, line rates, and frame rates, in addition to a variable pulse width. The proper application of pulse modulation is shown to have merit in reducing the interference effects associated with continuous wave systems.

FOREWORD

This report describes the development of an experimental pulse modulated, ultrasonic imaging system built for nondestructive testing applications. It includes an account of the system concepts and instrumentation as well as details of the image tube and transducers. Circuit details of the electronic instrumentation are described in a separate report.

This system represents one of many concurrent tasks in the Frankford Arsenal research and development program on Ultrasound Imaging Techniques. The program involves the exploration of new transducer designs, modulation techniques, data processing methods, and display configurations.

The instrumentation described herein was designed and built by IIT Research Institute, Illinois Institute of Technology, under Contract No. DA-36-038-AMC-2813(A). The contract was initially under the direction of W. E. Lawrie and work has been completed by H. B. Karplus. The electronic design was carried out under the direction of Blayne Arneson.

TABLE OF CONTENTS

LIST OF FIGURES

DEVELOPMENT OF AN ULTRASONIC IMAGE CONVERTER

1.0 ULTRASONIC IMAGING PRINCIPLES

Pictures of hidden structures may be obtained by using some kind of radiation which penetrates the structure, but is differentially absorbed, scattered, or otherwise changed in its significant features. The commonest example of such a system is the X-ray. The radiation is there detected by a photographic plate sensitive to X-rays. After suitable development, visible pictures of previously hidden structures appear.

Ultrasonic vibratory radiation will also penetrate solid objects and has been used in this manner for inspection. One favored application is the inspection of metallic or non-metallic work pieces for flaws. In many instances ultrasonic techniques compete with X-rays. Advantages of ultrasonics over X-rays are:

1. The elimination of time delay and cost of film development, and
2. Bond failure normal to the plane of inspection are very difficult to detect with X-ray but give particularly strong indications with ultrasonic inspection. X-rays detect only a change in material quantity. Ultrasonic transmission is affected by discontinuities.

X-rays are usually made visible by means of photographic film. Photographic film has very low sensitivity to ultrasonic radiation, requiring very long exposure at very high intensity to yield appreciable blackening. This system has not been utilized for making defects in most pieces visible. Instead, a more complicated system has been worked out which has the advantage that pictures are more quickly available by means of a television type display.

The system consists of a tank filled with water as a medium to support propagation of acoustic energy, a transmitter to generate the acoustic energy, the test object, and a piezoelectric receiver.

The receiver is mounted on a plate in one wall of the tank and the remote side is evacuated. The sound energy falling on the receiving transducer produces piezoelectric charges on the face of the transducer. The instantaneous charge at any point on the transducer surface is proportional to the instantaneous sound pressure at that point.

An electron gun is used within the evacuated space to direct an electron beam to the receiver and scan it point by point. Secondary electrons generated by the electron beam are collected by a high voltage collector in the enclosure. The electron current to this collector is now modulated by the varying charge on the receiver thus yielding an alternating electrical signal on the collector proportional to the intensity of the sound at the point being scanned by the electron beam. The alternating electrical signal at the collector is amplified, rectified and then used to modulate the beam of a television type display tube. The deflection of the display tube beam and scanning tube are synchronous so that light and dark areas correspond to high and low intensity regions of the sound of the ultrasonic receiver.

2.0 PULSED OPERATION OF THE IMAGE CONVERTER

In most instruments constructed in the past, continuous ultrasonic waves were used. The instrument constructed on this program utilizes short pulses of ultrasonic energy. This has the significant merit that energy arriving at the detector by indirect paths can often be ignored.

When continuous waves are employed, sonic energy will reach the receiver by various paths after refraction, reflection and scattering at interfaces in the test specimen. All these waves will interact and give rise to complex interference patterns due to the coherence of the transmitted wave. These interference patterns obscure patterns to be observed. Some improvement by various devices have been used: for example, frequency modulation of the transmitted energy can be used to reduce the sharpness of the interference pattern, permitting superior picture definition.

The approach used on the apparatus described here eliminates the interference problem by supplying the sonic energy in short bursts. Waves travelling by different routes arrive at the receiver at different times. For this reason no interference patterns are established. In addition, the receiving circuit contains an electronic gate which is open for a brief period only when the directly transmitted pulse arrives. By this means the indirect sonic pulses are excluded from the receiving system.

An additional advantage of this gated pulse system is the elimination of adverse effects of direct electrical coupling between transmitter and receiver. With the metallic tank used, some direct pickup of the transmitted pulse by the receiver was not completely eliminated. Such direct pickup adversely affects continuous wave systems, but in the pulsed system this direct coupling is eliminated by the gate together with other extraneous signals.

Provision has been made to switch off the pulser unit and connect the oscillator to an external power supply. However, better electrical isolation between the transmitter and receiver may be necessary to obtain an acoustic signal well above the electromagnetic leakage.

A system was described by Prof. Jacobs of Northwestern University at the November 1967 meeting of the Acoustical Society in which the phase of the received acoustic signal of a continuous wave system is used to control the color of the display. This color system seems to be a significant advance in continuous wave image converters. It seems quite likely that this scheme may also be adapted to the type of pulsed converter developed on this program. However, it would seem to be quite a major task. The absence of interference phenomena in the pulsed system is considered to be by itself a significant advance in ultrasonic imaging.

3.0 APPLICATIONS

Ultrasonic image converters have been used predominantly in two areas: nondestructive testing and bio-medical applications.

In nondestructive testing, flaws in work pieces can be observed by virtue of the sonic energy scattered by them. The most successful results have been obtained in laminar structures where poor bonds will produce strong acoustic shadows and where alternative forms of inspection such as X-rays are very poor because the total mass in the path of the X-rays remains constant. Special techniques have been used in continuous wave systems in which thin structures are placed at an angle to the sound beam so as to excite Lamb waves in the specimen. This reduces the interference problem in continuous wave systems. Similar techniques may be desirable also for the pulsed system although the need is less severe.

If thick objects are examined with the pulsed imaging system, the change in the time delay of the pulse traversing the work piece must be compensated by a corresponding change in the gate delay of the receiver. If parts of an object have different thickness, these parts may be examined separately.

With the shortest available pulses on the present system, metal objects in water varying by less than 1/4 in. in thickness can be observed with the same gate setting. For objects varying in thickness by more than this, either longer pulses must be used or different parts of the object must be examined separately. It should be noted that the sharpness of the shadow cast by any defect deteriorates as the distance between the defect and the receiving transducer increases. The minimum distance between the object and the receiving transducer is set by the thickness of the faceplate on which the receiver is mounted. The object to be examined should always be placed as close as possible to the receiver to achieve the best resolution.

For biological applications, the high absorption of the sound wave in the tissue reduces the severity of the interference phenomena when continuous waves are used. The pulsed system has therefore more significant merit in the nondestructive testing applications.

4.0 GENERAL DESCRIPTION OF THE IMAGING SYSTEM

The basic components of the instrument are:

- A converter tube mounted on the side of a large water tank and connected directly to a large vacuum system below it.
- A generator of ultrasonic energy mounted in a small brass box and connected to the electronic supply via a flexible cable.
- A cathode ray display tube for image read-out, mounted on the main electronic rack together with necessary amplifiers, controls, sawtooth generators, etc.

The electronic control unit contains five rack panels, Fig. 4.0. The lowest unit is the control panel for the Ultek Vac/Ion Pump. The fourth panel (immediately above the pump unit) contains power supplies. Switches on this permit switching off all the electronics while leaving the image converter filament on.

The third panel contains the pulse generator and the basic time generators, pulse repetition rate control, pulse duration control, deflection generators, and the control for the gate of the receiving amplifier.

The second panel contains the main electronics power supply switch, operating via a relay. Also on this panel are the image converter heater control and heater voltage indicator and the collector potential adjustment and collection voltage and current indicators.

On the top panel is the oscillograph display tube and its controls (black knobs); on the right side are a group of white knobs for the corresponding controls of deflection amplitude and position, intensity and focus for the image converter

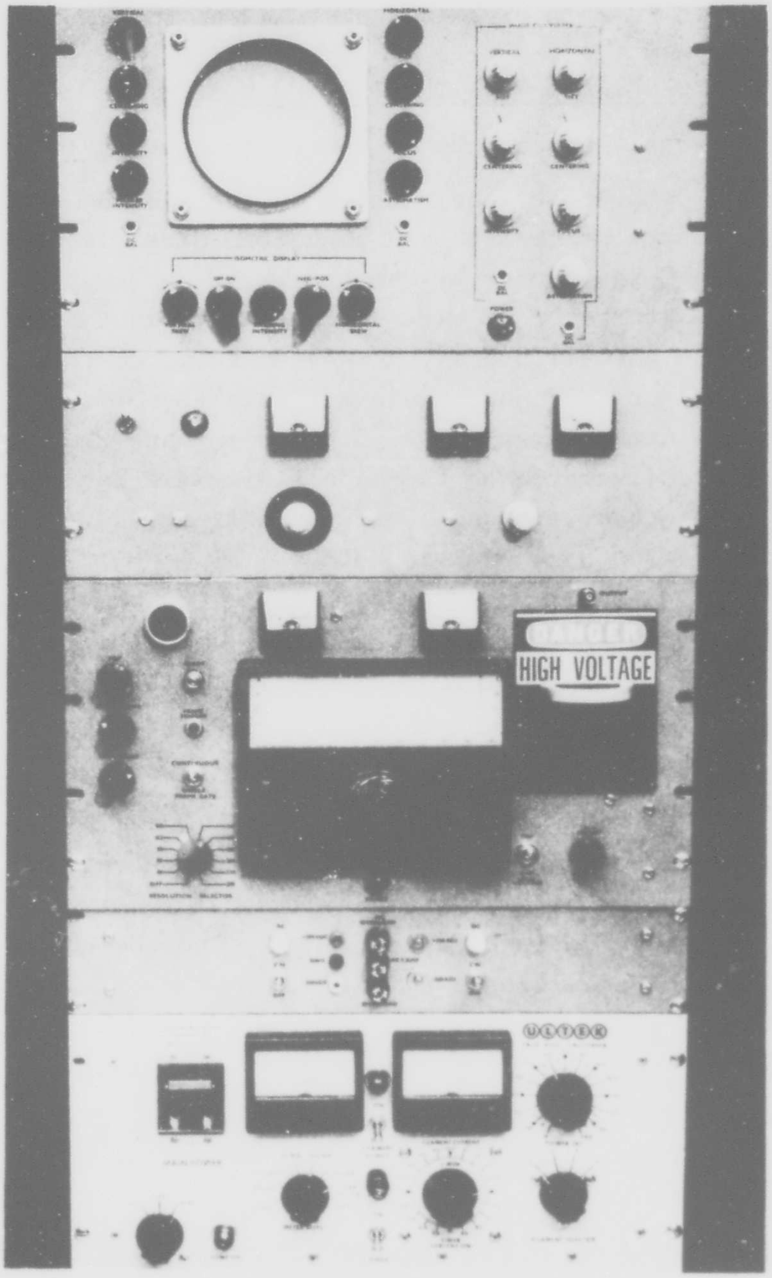


Fig. 4.0. **ELECTRONIC CONTROL UNIT.**

The Panels are from the Top Down:

Display Chassis

Power Control

Pulser and Logic Card Chassis

Auxiliary Power Supply

Ultek Boostivac Pump Power Unit

unit. Below the image display tube is a central knob marked shading control which is the overall gain control for the signal. This combined with the brightness control of the display tube governs the contrast of the final image. An additional group of controls adjacent to the main shading control permit a display which gives the image an appearance of a three-dimensional projection. This is accomplished by coupling some of the signal to the vertical deflection and interconnecting the horizontal and vertical deflection. The latter produces a skewed image and the former produces a vertical deflection instead of, or in addition to, a brightening of the trace proportional to the received sound intensity. In practice it has been found that this form of display has rather limited utility for large signals because of the overlap resulting on adjacent lines. For small signals the variation is somewhat more apparent than the simple brightness variation. However, with sound generators of limited size, the sound field is not sufficiently uniform to really take full advantage of this feature.

4.1 THE CONVERTER TUBE

The overall view of the apparatus at the front of the report shows the image converter tube mounted to the side of the coupling tank and connected to the pump unit through a side branch. An exploded view of this unit is shown in Fig. 4.1.

The tube consists of a stainless steel cylinder with an external and an internal flange at one end and a tapered section at the other. The tapered section is joined to a glass section and this in turn connects through a suitable variation in glass composition to a ground glass cone. The mating male cone holds ten wires sealed into the glass end plate. These wires terminate internally in small brass sleeves and externally in an 11 pin socket. The gun for a 2AP1 cathode ray tube is

Fig. 4.1 EXPLODED VIEW OF ULTRASONIC IMAGE CONVERTER TUBE.

fastened to the brass sleeves as shown. Care must be taken when assembling the gun to the base that the filament wires are connected to the pins adjacent to the key on the plug. The gun is intended to be installed with the rear plates horizontal (vertical deflection) and the key on the plug upwards.

A side branch on the converter tube is connected to the pump system using either a copper or a viton gasket. If a copper gasket is used, the bolts must be tightened to 20 ft-lb to assure a good seal.

The external and internal flanges at the front of the converter seal the tube to the tank and the faceplate to the tube respectively. The tube is held on the tank with machine screws. Sealing is accomplished with a rubber "O-ring." The vacuum seal between the tube and the faceplate is also accomplished with an O-ring. The faceplate is held in position by the atmospheric pressure and the hydrostatic pressure in the tank.

Immediately behind the flange holding the faceplate and receiving transducer a fine mesh screen can be seen in Fig. 4.1. This screen is in metallic contact with the tube envelope and thus always at ground potential. The screen is required to eliminate electrostatic coupling between the transducer and the collector. The electrostatic coupling would be equally effective for all points on the transducer whereas the electron beam coupling is confined to one small spot at any instant.

Not visible on this picture are two large rings mounted on externally accessible glass seals. One of these rings is connected to the preamplifier via a coupling capacitor and to an adjustable positive potential via an isolating resistor. Meters on panel 2 indicate the voltage and current used by this collector.

The other ring may be either connected to ground or in parallel with the first ring. Not much difference in operation could be discerned either way.

In normal operation the image converter is left permanently bolted to the tank and the vacuum system. The faceplate-transducer assembly is changed every time the operating frequency is to be changed. Three faceplates with transducers mounted on them have been supplied.

4.1.1 Faceplates and Transducers

Three transducers have been supplied; these are nominally 1, 2.5, and 5 MHz. The transducers have each been bonded to their respective faceplates so that changing frequency requires simply removal of a faceplate-transducer assembly and replacement by the desired one.

Faceplates are made of glass 0.22 in. thick. Glass was chosen and covered on the edges surrounding the transducer with phosphor so that focus and beam alignment may be checked by deflecting the beam a small distance beyond the transducer. This facilitates adjustment of focus and astigmatism controls and setting of the position and amplitude controls. The thickness was chosen to give the plate little distortion under the operating condition of slightly over one atmosphere pressure difference.

The transducers are bonded to the faceplates with a mixture of beeswax and rosin obtained from the lens grinding shop. The mating surfaces of the faceplate and the piezoelectric transducer element were metallized with chrome and gold by evaporation in vacuo. The metal deposit on the glass projects beyond the transducer and must be installed so as to contact the small grounding leaf spring inside the converter tube.

The 1 MHz and 2.5 MHz transducers are single slabs of PZT 2.5 by 2.5 in. with thickness ground to the respective resonant frequencies.

The 5 MHz transducer is a 2.5 by 2.5 mosaic array made of 6 quartz crystals 1.25 by 0.833 in. each. These crystals are cut with the X-axis in the thickness direction, the Z-axis parallel to the 1.25 in. sides, and the Y-axis parallel to the 0.833 in. side. No precautions were taken to ensure a uniformity in the sense of the direction of the X-axis. Since only one spot is examined at a time, this is not important; although for those points for which the beam is divided between two crystals, a reduction in output can be expected if the crystals are in opposite directions. This direction of the crystal axis is of importance in the transmitting transducer where opposite facing crystals would yield very non-uniform fields. For the transmitter the crystals have been aligned as discussed in the appropriate section.

4.2 THE VACUUM SYSTEM

The vacuum system consists of:

1. A fore pump Welch Duo Seal Type 1402,
2. A fore line trap with bakeout heater,
3. A vent valve ("C") for venting this system to the atmosphere,
4. A fore vacuum thermocouple gauge,
5. A 1-1/2 in. line valve ("B") between the converter and fore line,
6. A 2 in. line valve ("A") connecting converter to the high vacuum pump,
7. A high vacuum pump Ultek Model 10-402.

The high vacuum pump is an ion pump with titanium booster sublimators. This pump is controlled from the lowest panel on the electronic rack. The bakeout heater switch for this pump and the controls for the fore pump are on a sloping panel on the vacuum unit. A schematic of the valves is shown in Fig. 4.2.

In normal operation the high vacuum pump is evacuated at all times. When the faceplate or electron gun are changed in the converter, the main line valve "A" is closed so that the converter may be brought up to atmosphere by opening valves "B" and "C."

The pressure under normal operation is monitored by reading the pumping current in the ion pump. During normal operation the fore line valve "B" is closed and the fore line brought up to atmospheric pressure by opening valve "C" and turning off the fore line pump.

4.3 TRANSMITTERS

Three transducers are provided for operation at 1, 2.5, and 5 MHz. The 1 MHz and 2.5 MHz transducers are made of a single slap of PZT silvered on one side and chrome and gold plated on the other. They are housed in brass boxes with coaxial leads. The boxes are large enough to hold tuning coils to which access is provided through O-ring sealed cylindrical projections. No great merit was found in using additional coils. The output was not increased, only the tuning setting of the oscillator is changed. If very long cables are used (of the order of one-eighth wavelength, i.e., over 125 ft at 1 MHz over 25 ft at 5 MHz), matching the end of the cable would result in significant improvement. With the short lengths of cable provided, this additional tuning was abandoned. One such transducer is seen resting on the pump unit in the overall view at the front of this report.

The 5 MHz transmitter uses a different construction. Radiation uniformity could not be obtained using PZT. Moreover, the transducer was extremely fragile and many were broken in

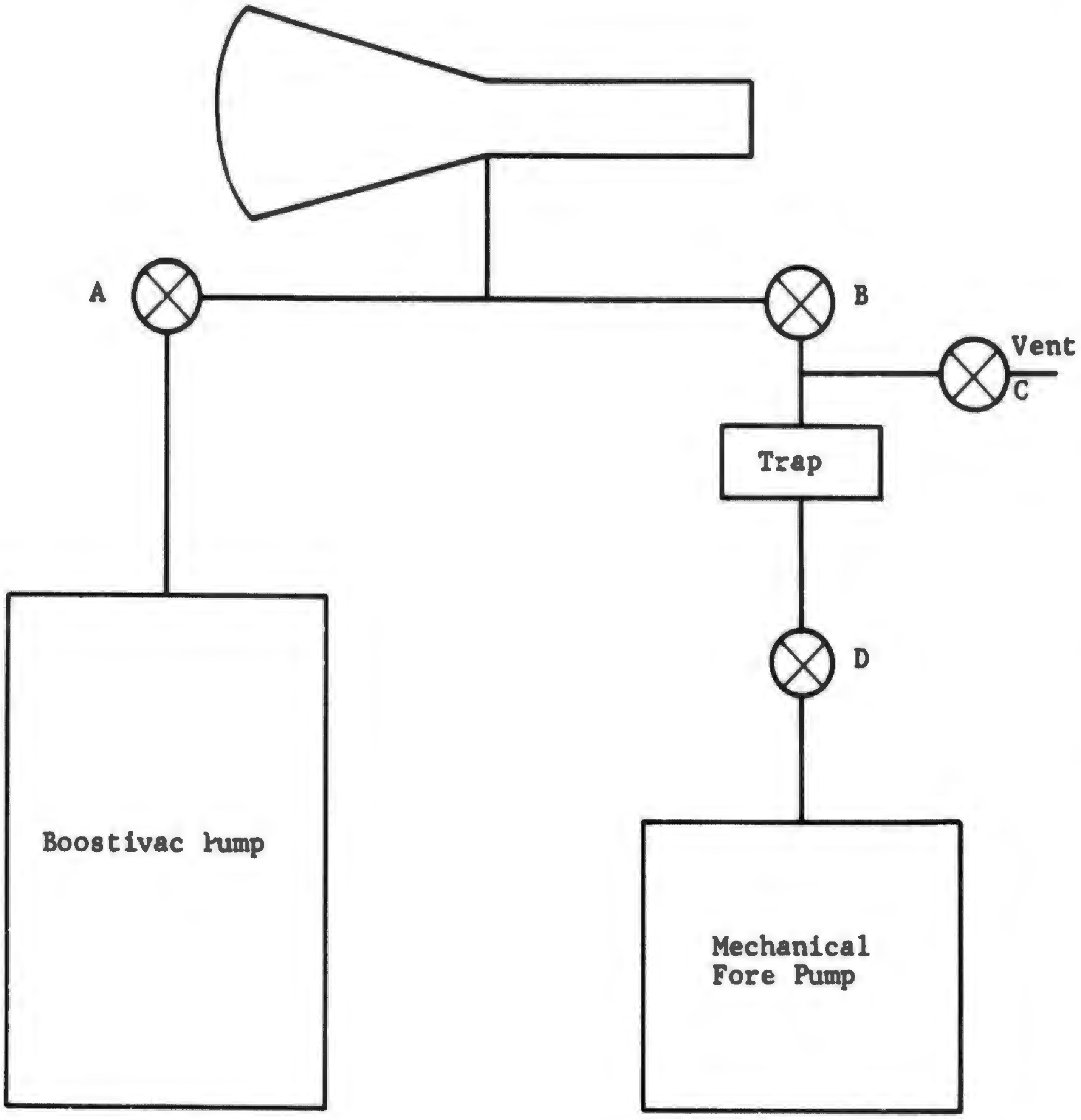


Fig. 4.2 CONNECTIONS OF VACUUM PUMPS TO IMAGE CONVERTER.

the attempt of constructing one. Ultimately, a mosaic of quartz crystals was used. These were separated from the water medium by a brass plate one-half wavelength (0.0185 in.) thick, Fig. 4.3.

It was thought that optimum transmission would be achieved by using two quarter wave plates of materials of very different impedance. Accordingly a double layer was made of mylar (0.006 in.) and stainless steel (0.012 in.). The resulting transducer had lower output and poorer uniformity than the single half-wave plates of brass. The reason for this is not certain.

Computations of Fry and Dunn had indicated that this configuration should yield optimum output. The failure might possibly be due to the limited bandwidth obtainable with this optimum configuration so that for pulse work the half-wave brass was used in accordance with the empirical findings.

One precaution needs to be observed if for any reason the transducer has to be serviced. The quartz crystals are asymmetrical and must be aligned so that the same voltage on all produces a displacement in the same sense in each crystal. To check this the following procedure was used.

The crystals were placed on an insulated metal plate connected to the input amplifier of an oscilloscope. Light tapping of each crystal should then produce a deflection in the same direction. If any crystal produces a deflection in the opposite direction, it should be inverted so that the other face touches the pick-up plate.

To facilitate this observation the oscilloscope time base was triggered at the instant of impact by connecting the impacting tool to the external trigger input terminal via a 100 ohm resistor to a six volt battery. The other battery terminal was grounded. A 1000 ohm resistor from the trigger terminal to ground improved stability. The upper surface of the crystal was grounded using some aluminum foil. Contact

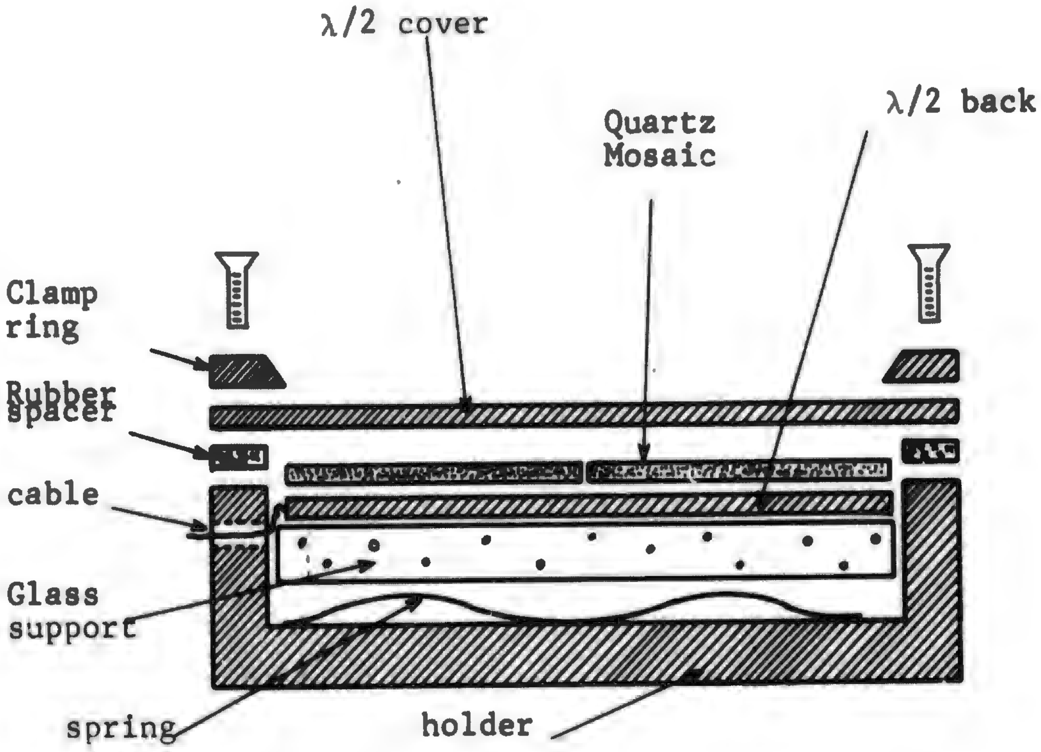


Fig. 4.3 Holder for 5MHz Transmitter

between the small impact tool and the ground brings the voltage of the trigger input terminal rapidly from 5.5V to zero, providing the trigger pulse. The use of single sweep oscilloscope is desirable to avoid retriggering on bounce, but this is not essential. Further simplification of this observation is possible by the exercise of some ingenuity. For example, the system just described works quite well using the assembled transducer. The transducer is simply plugged into the vertical input terminals of the oscilloscope and the front face is lightly tapped with a metal rod connected to trigger input via a battery as mentioned before. The interposition of a small block in front of the transducer face will delay the acoustic signal a few microseconds making the initial step due to the impact more easily visible on the oscilloscope.

4.4 THE ELECTRONIC SYSTEM

The principles of the electronic system are discussed in this section to the extent to which they are of general interest. A more complete description of the system is given in Part II. This will be of interest to engineers needing to service or duplicate the system.

The electronic system is arranged on four standard 19 in. rack panels supplemented by a small preamplifier mounted close to the image converter. A block diagram is shown in Fig. 4.4.

4.4.1 The Display

The top panel contains the image display cathode ray tube and the position and amplitude controls for the electron beam in the display tube and in the converter tube. The controls are color coded. White knobs are used for the converter tube controls and black knobs for the display tube.

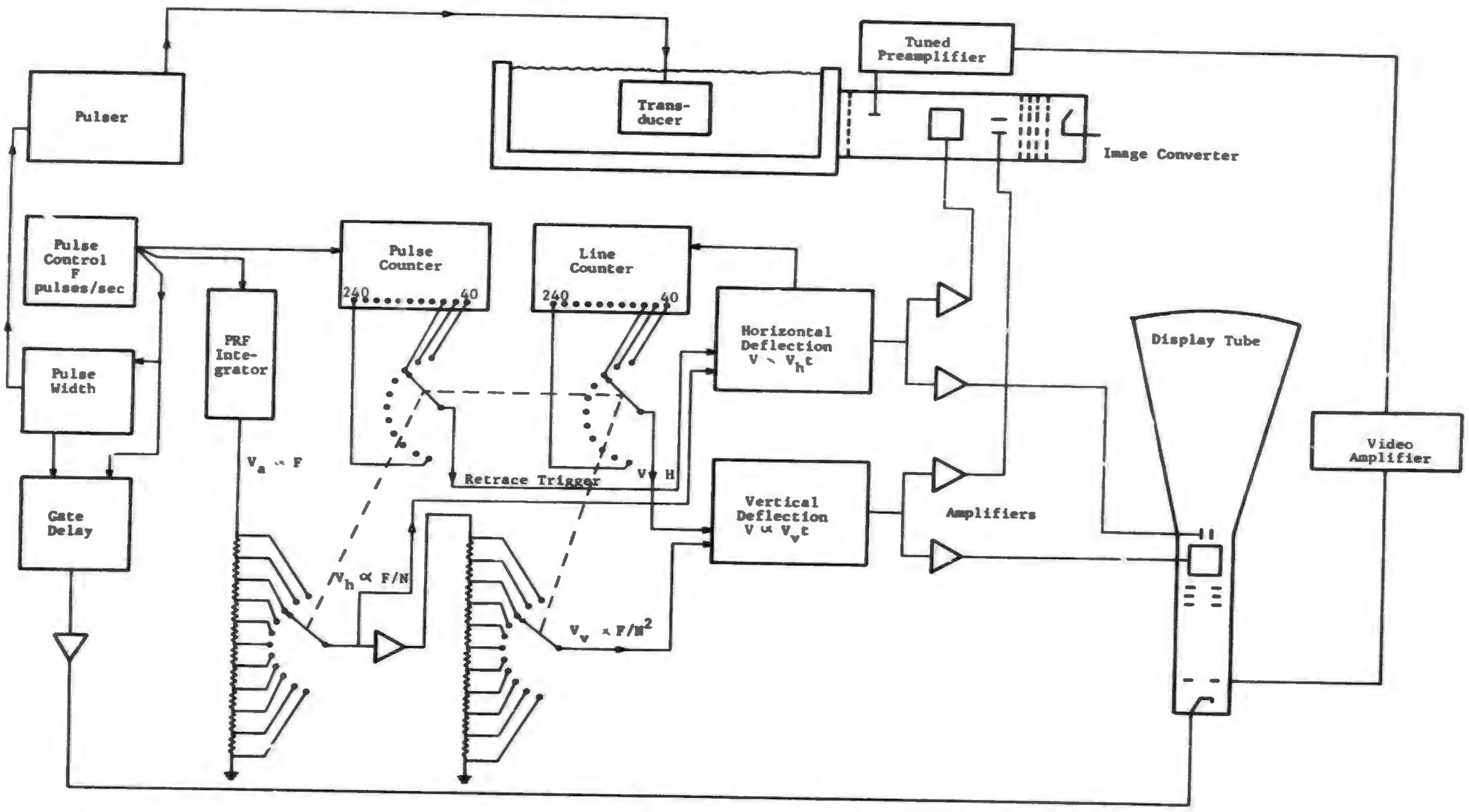


Fig. 4.4. Block Diagram of Electronic System

Under the cathode ray display tube is another set of controls to adjust the character of the display. The central knob marked "shading" is the principal gain control for the system and controls the contrast in the display. Turned counter-clockwise the picture becomes fainter. Turning the control clockwise increases the highlights, until overload occurs and only very "dark" shadows will show up. (Somewhat similar effects may, of course, also be produced by the adjustment of the power of the transmitter. Both amplitude and pulse width have similar effects.)

4.4.1.1 Isometric Display

A special feature designed into the system permits a rather unusual form of the display. By turning the switch next to the shading control "On," the raster appearing on the display tube is changed from a square to rhombus and some of the signal is injected into the vertical deflection. In this way the picture looks like a topographical map seen at an angle. The amount of vertical and horizontal skewing can be controlled from knobs adjacent to the controls just mentioned.

The signal can be arranged to produce bright hills or dark valleys by throwing the switch between the shading control and the horizontal skewing control from "pos" to "neg."

4.4.1.2 Single Frame Feature

When taking photographs of the display it is desirable to photograph an exact whole number of frames. If the camera shutter is opened for a period not an integral multiple of the picture period, one part of the picture will be exposed longer than the remainder. A switch, push button and light on the front panel permit a single frame to be recorded. With the switch in the "manual" position, the vertical sweep is initiated manually by pushing the button. A ready light comes on when the picture has been completed. The procedure for taking pictures is then:

1. Switch to manual,
2. Wait for ready light to come on,
3. Open camera shutter,
4. Push single frame button,
5. Wait for ready light to go out and come on again,
6. Either repeat steps 4 and 5 a desired number of times, or proceed to
7. Close camera shutter.

4.4.1.3 Electronic Graticule

Because of the digitized control of the deflection circuitry, a very simple electronic graticule was included with the device. Every twentieth pulse of each line and every twentieth line of each frame is brightened, giving a rectangular array of markers. Full control from zero to maximum intensity is available by means of a "Marker" control below the "brightness" control of the display tube.

4.4.2 The Gate Circuit

One of the main advantages of the pulsed imaging is the ability to eliminate all sound waves arriving at times other than the interval when the directly received pulse arrives. This is done by turning the display tube off except during the brief interval when a pulse is expected. The cathode of the display tube is normally at a less negative potential than the grid so that the screen remains dark even if a signal arrives. During the expected arrival time of the pulse, the cathode is driven sharply negative. With proper adjustment, adjustment of the brightness control and the shading control, any desired contrast can be obtained within the limits of the properties of the display tube phosphor.

In practice it has been found that a photograph can show small variations more clearly than are visible by direct viewing of the screen.

The gate circuit is controlled by two flip-flop circuits. The first one is initiated by the same pulse which triggers the sound generator. A front panel control marked "Gate" controls the time before switching back. This switching back initiates the start of the gate pulse. At the same time an additional monostable Flip-Flop is switched which on switching back terminates the gate pulse. The gate width control flip-flop is almost identical to the flip-flop generating the initiating pulse to the transmitter and both are controlled by a pair of ganged 25K potentiometers marked "Pulse Width" on the front panel. This assures that widening the transmitted pulse widens the gate pulse at the same time. Internal labeled screwdriver adjustment controls permit setting the minimum pulse width and gate width with the panel control in the minimum counterclockwise position. The internal adjustments are 5K "trimpots" in series with the 25K front panel controls.

4.4.3 The Deflection Circuitry

The deflection circuitry is somewhat unconventional to assure precise repetition of the position of pulses from frame to frame. This was done to permit connection of the system to a computer to analyze defects automatically. The objective is achieved in the following manner.

The horizontal and vertical deflection generators produce deflections which are synchronized with the basic pulse rate generator. The deflection rate is controlled by a front panel control which determines the number of pulses emitted during one horizontal scan and the number of lines in a vertical scan. The resolution can be set in increments of 20 pulses from 40 through 240 pulses per line and an equal number of lines per frame. The receiving transducer is 2.5 by 2.5 in. Resolution in the horizontal and vertical direction are therefore the same. The retrace is triggered from a scale of 20 counts so that this is always precisely set. The "Resolution" switch simply selects the number of times twenty counts have occurred before resetting the deflection.

The resolution switch, of course, also has to control the sweep rate of the deflection circuit so that the picture size remains constant. The horizontal sweep rate must be proportional to the pulse repetition rate and inversely proportional to the number of pulses to be counted before retrace. This is accomplished by generating the sweep voltage, $V_{i,h}$, using the integration of a constant potential, V_h.

$$V_{i,h} = K \int_0^t V_h dt = KV_h t .$$

The integrator is a conventional operational amplifier having capacitive feedback and resistive input. The proportionality factor K is fixed by the value of the capacitor and resistor externally connected to the operational amplifier.

The sweep rate is changed by changing the bias voltage V_h. Since the sweep rate must be proportional to the pulse rate and inversely proportional to the number of resolution elements, the voltage V_h is derived from a source which is derived from the pulse repetition rate and the resolution. A voltage V_a proportional to the pulse repetition rate is generated by integrating pulses over a fixed period. Thus, if F is the pulse repetition frequency,

$$V_a \propto F .$$

A precision voltage divider is ganged to the resolution control which takes a portion of this voltage and applies to the deflection integrator. Calling N the resolution selected

$$V_h = K\ F/N\ .$$

Since the retrace occurs after N pulses, this will take place at time $t_{oh} = N/F$, and the length H of the line is proportional to the deflection voltage at this instant

$$H \propto V_{i,oh} = KV_h t_{oh} = K \frac{F}{N} \frac{N}{F} = K\ ,$$

and thus independent of the pulse rate or the resolution setting.

The vertical deflection is retriggered after a fixed number of lines N equal to the number of pulses selected to initiate the horizontal retrace. Thus the duration t_{ov} of the vertical sweep must be proportional to N^2/F and the sweep rate inversely proportional to this factor. The vertical deflection voltage V_v is derived by an integrator similar to the horizontal integrator

$$V_{i,v} = K_v V_v t\ .$$

The voltage V_v is derived by an additional voltage divider following the horizontal voltage divider isolated from it by a buffer amplitude, $V_v = V_h N$.

The resolution control thus performs four functions by means of ganged switches:

1. It selects the number, N, of pulses received from the counter counting the pulses emitted.
2. It selects the same number, N, from a counter counting the number of lines scanned.

3. It attenuates the D.C. voltage from the pulse repetition rate integrator by a factor 1/N.
4. It attenuates the output of (3) by another factor 1/N.

4.4.4 The Preamplifier

The signal from the image converter is boosted by an amplifier located physically close to the converter tube. The capacitive reactance of the converter tube collector is tuned out by means of a switch selected coil and continuously variable trimmer capacitor to minimise circuit loading of the image converter output. The direct current taken by the collector is monitored by a meter on the second panel on the main electronics rack. The signal from the preamplifier is passed the amplifier and "shading intensity" control on the electronics rack to control the instantaneous picture element intensity of the display image.

4.4.5 The Pulse Generator

The design of the pulse generator is based on the design of the commercially available Arenberg pulse generator. The most significant changes are an increase in the power rating by using a more powerful tube and a supply with higher current rating.

A double pentode is used as the main oscillator. This is normally not conducting by application of sufficient bias. The pulse from the pulse control identical to the gate control flip-flop already mentioned turns the pulser on and off again after a preset interval.

A pair of diodes connected from the oscillator plates are back biased when current is flowing through the oscillator tube. When this current is switched off, the diodes conduct and short circuit the transducer to damp out ringing. A plug is provided in the coil compartment to disconnect the damping diodes. This is necessary if the oscillator is to be used to generate continuous waves.

In order to use the oscillator on continuous waves, the pulsed bias is removed and fixed bias substituted by turning a switch on the rear of the instrument. For continuous operation, an external power supply of about 400V, 250 ma capacity is required. Terminals for connecting it are also provided on the rear of the instrument. In this condition the plate current meter is also shunted to read 300 ma full scale.

The internal power supply used in the normal pulsed mode is adjustable to 2 KV by means of a "Variac" voltage transformer on the front panel, meters read both voltage and current. Also included is an audible alarm which warns the operator when 30 ma is exceeded. This feature is helpful during operation in a darkened room when reading the monitoring meters may be inconvenient.

Oscillator frequency is changed with plug-in coils behind a protective plate on the front panel. A microswitch disconnects the high voltage when this panel is removed. However, it is advisable to turn down the voltage with the Variac and check the panel meters. The voltage decay takes several seconds when the input is opened by removal of the protective panel.

Separate coils are used for each of the frequencies of the transmitters supplied. Fine tuning is effected with a parallel tuning capacitor. The dial of the tuning capacitor was left unmarked as the tuning has to be readjusted when the voltage is changed.

5.0 RESOLUTION OF REMOTE OBJECTS BY THE IMAGE CONVERTER

The resolution of detail in the image produced by the converter depends on the wavelength of the sound and the distance between the receiver and the scattering object. The computations of the precise nature of the scattered sound field are quite complicated and depend on the shape of the scattering object and the exact wave front shape of the irradiating sound. We confine ourselves here to some approximate estimates which yield the order of magnitude of the detail which can be observed.

To estimate whether two small objects, major linear dimension, a, separated by distance, b, can be distinguished as two separate objects, we use the Rayleigh criterion for telescopes that the angle, θ, between the objects subtended at the receiver should be at least equal to the effective aperture λ/a. Now, if the distance, d, between the objects and the receiver is large compared with the resolution dimensions a,b, then the angle θ is approximately b/d. Thus

$$\begin{aligned} \theta &= \lambda/a \\ &= b/d \\ ab &= \lambda d \end{aligned}$$

Now if one distinguishable picture feature is considered to be a + b, then for a fixed product ab the sum will be a minimum when $a = b = \sqrt{\lambda d}$. We thus take $\sqrt{\lambda d}$ as the resolution criterion for the system.

Now in normal operation the distance d is made up of three parts: the distance between the defect and the edge of the sampel, d_s; the distance between the edge of the sample and the receiver, d_w; and finally the thickness of the glass faceplate, d_g. The wavelength in the three media is invariably different and refraction takes place at each interface.

Without introducing any additional errors of any consequence, we can write the total effective distance d_m in a medium with sound velocity c_m in terms of the actual distances

$$d_m c_m = d_w c_w + d_s c_s + d_g c_g$$

Furthermore, we substitute for the wavelength λ_m:

$$\lambda_m = c_m/f \ .$$

So that the expression for the resolution becomes

$$\lambda_m d_m = d_m c_m/f = (d_w c_w + d_s c_s + d_g c_g)/f$$

Values computed for different frequencies are shown in Table 5.1.

Table 5.1

Predicted Resolution a + b (in mm)

Distance, mm				Frequency, MHz		
d_g	d_w	d_s	c_s/c_w	1	2.5	5
5.8	0	0		5.4*	3.4*	2.4
0	20	0		5.4*	3.4	2.4
5.8	20	0		7.6	4.8	3.4
5.8	0	5	4			
5.8	100	0		13.4	8.5	6.0
5.8	0	25	4			
5.8	60	10	4			

---

*Assumption $d \gg a$ is not valid.

6.0 DEMONSTRATION OF IMAGE CONTRAST WITH PULSED SOUND

The illustrations Fig. 6.1 and 6.2 show the advantage of the pulse operation. A one inch thick aluminum block with two holes through it was set up in front of the image converter. By setting the gate at $t_1 = L_w/c_w$, the time taken for the pulse to reach the receiver, a deep shadow is seen in the position of the block, Fig. 6.1. The gate delay is then reduced to $t_2 = (L_w-L_a)/c_w+L_a/c_a$, that is the time taken for the sound to reach the receiver after traversing the water as far as the block and then proceeding through the block at a higher velocity. The effect is shown in Fig. 6.2. Now only the part of the picture in the shadow before, is bright. Sound waves travelling outside the block do not contribute to the picture. The holes in the block stand out, however distortion and diffraction phenomena are observed. There is some indication of a defect even in Fig. 6.1 where at first sight none would be expected.

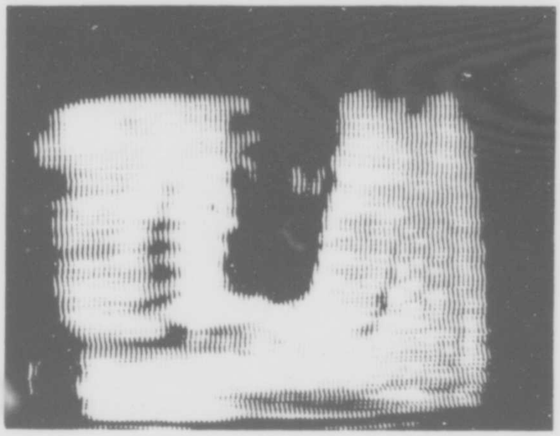
The phenomenon here is explained by a multiple reflected sound beam. After traversing the block, the pulse reaches the receiver while the amplifier gate is closed, leaving a shadow in the region. Some of the sound is reflected from the far face of the specimen, back into it with subsequent reflection again at the hole. The sound travelling the distance between hole and sample edge three times arrives at the receiver at nearly the same time as the pulse travelling through the water the whole way thereby getting through the "gate."

The condition that the reflected pulse arrives at the correct time may be expressed in terms of the block thickness, L_a, and the distance, L_d, of the defect from the remote surface, the respective velocities c_w, c_a in water and the block and the duration t_p of the pulse and t_g the width of the gate:

$$(L_a + 3L_d)/c_a = L_a/c_w \pm t_o$$

where $t_o < t_p$, $t_o < t_g$.

Fig. 6.1
Shadow of
Aluminum Block
Resolution (80)



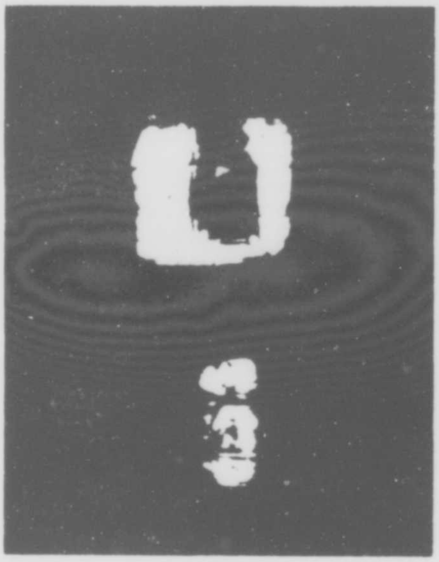


Fig. 6.3
As Fig. 6.1 & 6.2
Resolution (120)

Fig. 6.2
Transmission
through
Aluminum
Block

In general, of course, it is only possible to separate the two pictures, Fig. 6.1 and 6.2, if the block is thick enough with respect to the length of the pulse.

$$L_a/c_w + L_a/c_a > t_p + t_g$$

or

$$L_a > (t_p + t_g)\, c_w c_a/(c_w + c_a)$$

Typical values of c_a range from 5-6 km/s, c_w is 1.5 km/s, and $t_p + t_g$ is at least three microseconds. This yields a minimum block thickness for darkening the surrounding area by time separation of about 3.5 mm or 0.14 in.

Another picture was taken of the same block with a resolution setting of 120 using a different camera with a greater optical reduction. Here both frames with different delay times are shown, Fig. 6.3. In these pictures the outlines of the six individual 5 MHz crystals of the receiver mosaic can be barely discerned.

The isometric projection at different intensities is shown in Fig. 6.4. Individual line scans with two different delay times are shown in Fig. 6.5. Large signal variations are best seen on the straight intensity variation picture. For best isometric displays the intensity should be reduced considerably. Unfortunately it was not realized soon enough that better isometric displays are obtained with lower intensities to take superior isometric displays.

Fig. 6.4
Isometric Displays
at Various Intensities

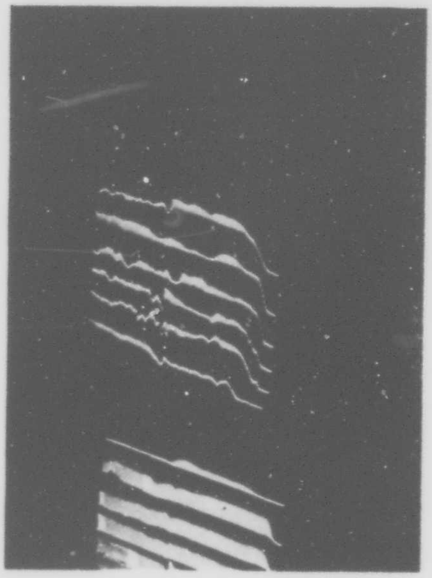


Fig. 6.5
Isometric Display on single lines
(Vertical size set at zero,
Vertical position controlled
manually.

7.0 PROJECT SUPPORTING DEVELOPMENT WORK

The limitations of ultrasonic imaging are prescribed by the finite wavelength of the sound used and the blurring of shadows due to diffraction at the edges of defects. A blurring of the simple shadow image occurs which gets worse as the separation between defect and receiver increases.

Acoustic lenses have been used for concentrating acoustic energy but relatively little work has been done in using them for image generation.

Acoustic lens design has the following merits and difficulties compared with optical lens design.

1. High refractive indices between solids and fluids are available permitting shallow lenses with low geometric aberration.
2. Image quality is usually diffraction limited so that the geometric aberrations have a relatively small effect. Consequently, fewer elements can be used. In fact it seems quite reasonable to use just a single spherical interface between the liquid transmission medium and a solid receiver support. (An IITRI In-house project, N1033, was the subject of the resolution capabilities of a single interface lens.)
3. Account must be taken of shear waves as well as compression waves generated in a solid for oblique incident sound waves. These shear waves in the lens will at subsequent interfaces give rise to compression waves and consequent spurious images.

In addition to image improvement by acoustic-optical means, work at higher frequencies would yield better resolution. A recent IITRI Project Suggestion 67-107MX describes a possible approach using shock waves. To make full use of the high frequency components in a shock wave, an image tube is suggested in which the image produced by shock wave is stored on the whole face of the receiver by an electron flood gun switched off immediately after the shock has reached the receiver. The stored charge pattern is subsequently readout at any desired speed.

Another possibility for improving image consists of a combination of the display of phase variation of the received signal by a color display together with the use of short pulses of sound described in this report.

The above suggestions merit further consideration, but will require extensive further development.

8.0 CONCLUSIONS

A pulsed ultrasonic image converter has been constructed, described, and delivered. Merits of a pulsed system are mainly the avoidance of interference phenomena usually found troublesome in continuous wave image converters. Basic limitations of the ultrasonic imaging technique relate to the finite wavelength of the sonic energy so that resolving power needs further improvement.

Resolving power is further limited by the spacing between the receiver and the defect to be detected. The use of a glass plate between the receiver and the medium further increases this distance. A compromise is necessary between the use of large detectors for rapid scanning and the mechanical strength needed to separate the vacuum from the atmosphere.

Ultimately it may be possible to design acoustic lens system in which the vacuum seal is part of a lens system to project images from the work on the receiver. It is suggested that ultrasonic imaging be improved by using lens systems instead of shadowgraphing and attempts be made to increase the sonic operating frequency.

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
FRANKFORD ARSENAL, Philadelphia, Pa. 19137
(SMUFA L3300)

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP
NA

3. REPORT TITLE
DEVELOPMENT OF A PULSE MODULATED ULTRASONIC IMAGING SYSTEM
Part I: General Description

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Research Report

5. AUTHOR(S) (First name, middle initial, last name)
KARPLUS, Henry B.

6. REPORT DATE
May 1968

7a. TOTAL NO. OF PAGES
41

7b. NO. OF REFS
None

8a. CONTRACT OR GRANT NO.
AMCMS Code: 5025.11.29901

b. PROJECT NO.
DA Project 1T024401A34901

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
Frankford Arsenal Report M68-28-1

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
This document may be further distributed by any holder only with specific prior approval of Commanding Officer, Frankford Arsenal, Philadelphia, Pa., Attn: SMUFA N3000.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Science & Technology Division
Army Materiel Command - AMCRD

13. ABSTRACT

The development of an experimental, pulse modulated, ultrasonic imaging system is described. Details of the image tube and transducer plus a general account of the instrumentation are given.

The system was designed to have a wide range of resettable pulse repetition rates, line rates, and frame rates, in addition to a variable pulse width. The proper application of pulse modulation is shown to have merit in reducing the interference effects associated with continuous wave systems.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Imaging Ultrasonics Nondestructive Testing						