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THE EFFECT OF CROSS-COUPLING ON THE TEMPORAL RESPONSE OF ULTRASONIC TRANSDUCER ARRAYS

by

David Hadley

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in the School of Photographic Arts and Sciences in the College of Graphic Arts and Photography of Rochester Institute of Technology.

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THE EFFECT OF CROSS-COUPLING ON THE TEMPORAL RESPONSE OF ULTRASONIC TRANSDUCER ARRAYS

by

David Hadley

Submitted to the Imaging and Photographic Science Department in partial fulfillment of the requirements for the Bachelor of Science degree at the Rochester Institiute of Technology

ABSTRACT

An investigation was performed examining a possible cause of acoustic cross-coupling in ultrasonic transducer arrays. It was postulated that pulse velocity was decreased due to the physical presence of other ultrasonic pulses in the medium. It was demonstrated that average pulse velocity is independent of the number of opposing waves traveling through an acoustic medium. A description of variable pulse velocity is discussed.

ACKNOWLEDGEMENT

The author would like to express his graditude to Dr. Kovacs of the Physics Department at Rochester Institute of Technology for all of his cooperation with regard to facilities and equipment.

Thanks goes to Bill Van Derveer for putting up with all of the escapades created in writing this thesis.

DEDICATION

To my mother. She taught me everything she knows about Fourier Analysis.

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LIST OF SYMBOLS

B = bulk modulus

C = celsius

d = distance between elements

$d2$ = d squared

D = depth of transducer

f = frequency

$k = 2\pi/\lambda$

$n = 1, 3, 5, \ldots$

p = density

dp = change in density

P = maximum density

s = standard deviation

t = pulse travel time

T = temperature

v = degrees of freedom

V = pulse velocity

$w = 2\pi f$

W = number of waves

x = position

y = position

Y = maxmium displacement

λ = wavelenth

I. INTRODUCTION

Acoustic imaging is the use of acoustical energy to propagate through an acoustically transparent media, refract and reflect with acoustically opaque material, and be detected by some means with coherent information obtained. It may be compared to imaging in the infrared, ultraviolet, microwave or x-ray portions of the electromagnetic spectrum. Using acoustical energy for imaging is quite different in the sense that it involves more than an extension of vision into the far reaches of the electromagnetic spectrum<1>. In that sense, acoustic imaging takes on the characteristics of electron optics by increasing the scope of vision into non-electromagnetic realms. Of course the final step of any imaging technique will regenerate the image information obtained into the domain of light in order to produce a final visual representation.

Acoustic imaging is indeed a uniquely different form of imaging. However, much of the essence of optical imaging carries over to acoustic imaging. The terms optics and optical are often used when describing acoustic imaging systems because equivalent terms have not come into common usage. One might describe the optics of an acoustical imaging system instead of referring to the acoustical lens system. The term optical path has a more widely conceived meaning than the term acoustical path, even though the two are equivalent. Newton's law of reflection <2> is the exact same equation in optical design as it is in acoustical lens design. Design problems are more complicated in acoustic imaging systems than in optical imaging systems because of the existence of two types of waves, specifically, longitudinal and shear waves.

A. ARRAYS

In phased arrays are facilitated in many aspects of imaging. These include radar antennas, sonar arrays, and medical ultrasonic imaging arrays. The objective of the arrays is to utilize a large number of small antenna elements to produce a beam which may be electronically steered and focused to illuminate an image at a desired spatial volume. First order treatment of arrays begins by assuming the individual elements in the array are completely uncoupled from one another.

Figure 1 illustrates an array being used as a near-field imaging structure. In the far-field of each transducer, at depths greater than $d2/\lambda$, the angular pattern is closely approximated by the spatial Fourier transform of the transducer. The topic of discussion here, however, is the physical existence of the waveform, not its shape. The effective width of the angular pattern is approximated by λ/d. In the near-field, the pattern is just the transducer output itself. This pattern will distort at some distance

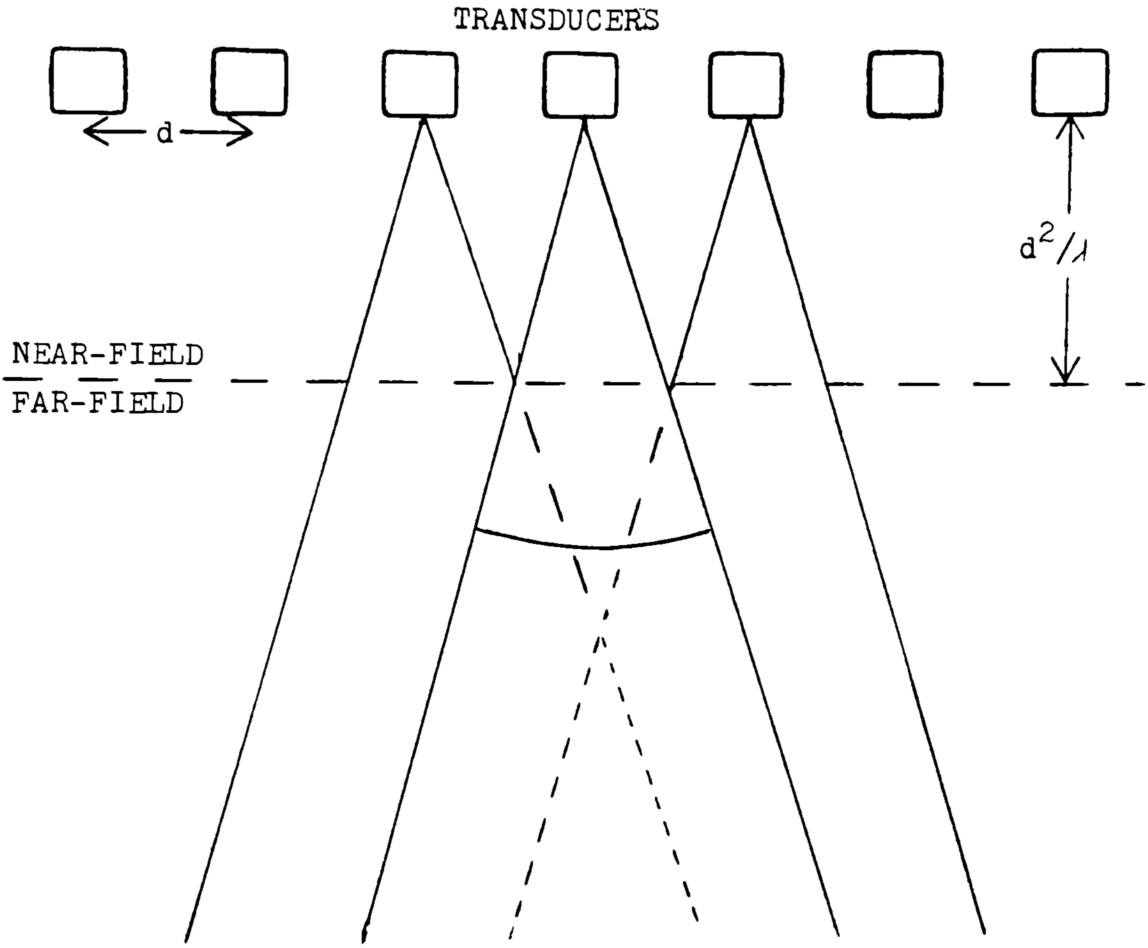

FIGURE 1.

TRANSDUCER ARRAY SHOWING DIFFRACTION SPREADING before the plane where the geometric projection intersects the far-field pattern corresponding to d2/λ. Therefore, for high resolution imaging a near-field set-up is adequate for only relatively short distances. Consequently, larger transducers which avoid excessive divergence in far-field regions are needed to image deeper into human anatomy and structural materials.

Phased array acoustic imaging systems are designed and operated on the basis of idealized models. In construction of such systems, unexplained phenomena of the actual device produce results that depart form the idealized theory. These results can be quite large<3>. The primary causes of departures from the ideal case are spurious vibration modes of the transducers and cross-coupling.

Radiation from an element is determined by the modes in which it vibrates. It is generally assumed that the elements vibrate in a one-dimensional "piston" mode. However, the modes at which the element vibrates may derivate greatly from this assumption. The actual modes of the acoustic elements have been widely discussed<4-12>.

B. CROSS-COUPLING

Cross-coupling is a phenomenon of phased arrays. It degrades the beam pattern and the temporal response of the transducers. Cross-coupling is found in multi-element arrays operating in the high ultrasonic range. One assumption stated earlier was that all of the elements in the array were uncoupled, meaning that the electrical excitation of the n'th element of any array resulted in acoustical radiation from only that element. In real world array systems, electrical excitation of the n'th element results in acoustical radiation from the n'th element, and to varying degrees, from all other elements in the array.

Cross-coupling occurs at two stages of the generation of pulse response. The first is electrical cross-coupling which is system dependent. Basically, electrical cross-coupling occurs when the drive electrical signal of one element can also appear on the other elements through inductive, capacitive, or resistive means. It could also take place via the cables connecting the elements to the receivers. For medical imaging arrays, working the 2-5 MHz range, the time delay between excitation of element n and the response of cross-coupled element m is quite small, probably measured in nanoseconds.

The second type of cross-coupling is acoustic cross-coupling. In the propagation media transmitted acoustic waves travel toward the receivers and interfere with one another, resulting in responses different than that of the uncoupled model. Time delay for acoustical cross-coupling is between the electrical excitation of element n and the acoustic response of element m. It is in the order of 1 to 10 microseconds and increases with the absolute distance between elements n and m. Acoustic cross-coupling is therefore situation dependent.

The effect of cross-coupling degrading image quality has been observed in a qualitative manner<13,14>. The hypothesis pursued here investigated the physical characteristics of many ultrasonic pulses traveling through a homogenous medium as a possible cause of acoustic cross-coupling.

C. CAUSES OF CROSS-COUPLING

The experimental hypothesis concentrated on a possible cause of cross-coupling. Loss in pulse velocity may be attributed to the actual acoustic waves in the system. Consider the physics of a tank of water with some means of creating ultrasonic disturbances. Acoustic waves are compressional waves traveling through an acoustic medium; in the case of our discussion, water. The velocity of such compressional waves depends on the compressibility of the medium and its density. Compressibility is the reciprocal of the bulk modulus. The velocity of propagation of longitudinal acoustic waves is:

$$V = \sqrt{B/p} \quad (1)$$

Density, p, is conventionally measured before the acoustic pulses are in the medium. However, consider an acoustic situation where the medium is full of compression waves. The returning acoustic waves must pass through the incoming waves to get back to the transducer. Figure 2 illustrates this point. To keep the ultrasonic disturbances straight in the discussion, the disturbance whose temporal response is being measured is called the pulse and the disturbances that the pulse travels through are called waves. The opposing semi-circular waves change the density of the water and make the medium non-linear. The opposing waves will slow down the returning pulses. Thus pulse velocity is not a constant value due to other pulses in the medium. See figure 3. Pulse velocity is not greatly impeded by passing through an opposing wave, however, if one considers present configurations of medical ultrasonic imaging arrays<15>, there could be 20 elements in a transducer operating at 1 MHz, at a distance of 10 cm, there would be 2666 waves that the pulse would have to pass through. Such configurations increase the number of opposing waves by three orders of magnitude.

Increasing the operating frequency and the number of transducer elements produces thousands of ultrasonic disturbances in the medium. The actual disturbances increase the functional density of the medium. An increase in medium density would decrease pulse velocity. This decrease in pulse velocity is a possible explanation for the unexplained delay involved in acoustic cross-coupling.

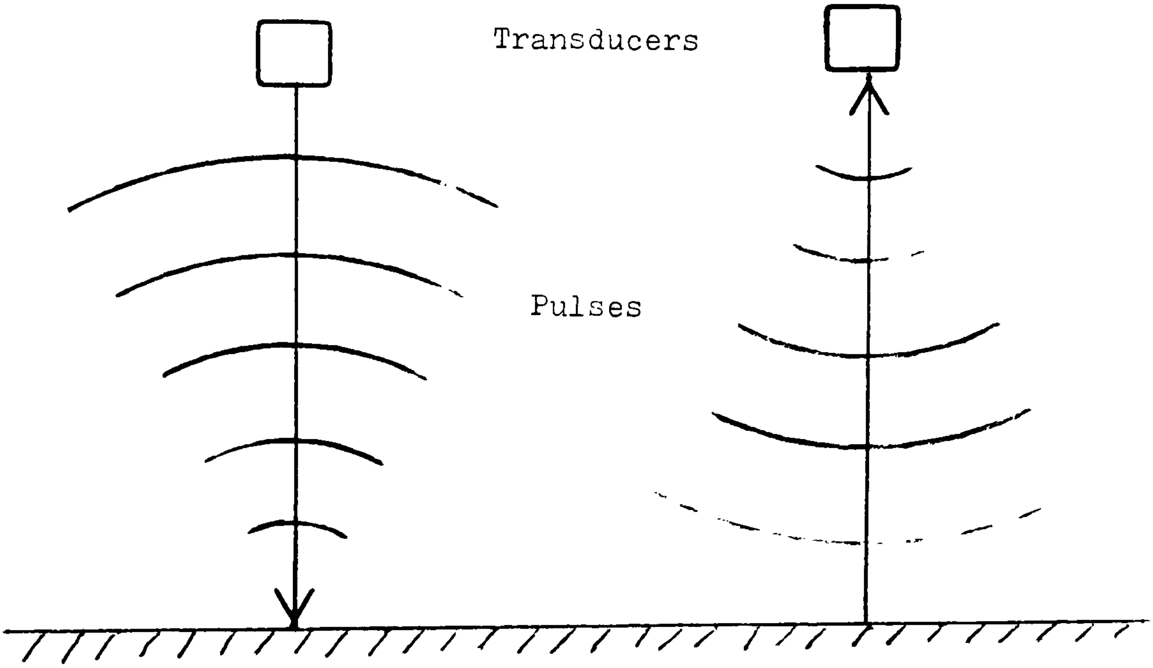

Figure 2.

Ultrasonic Pulses in A Medium

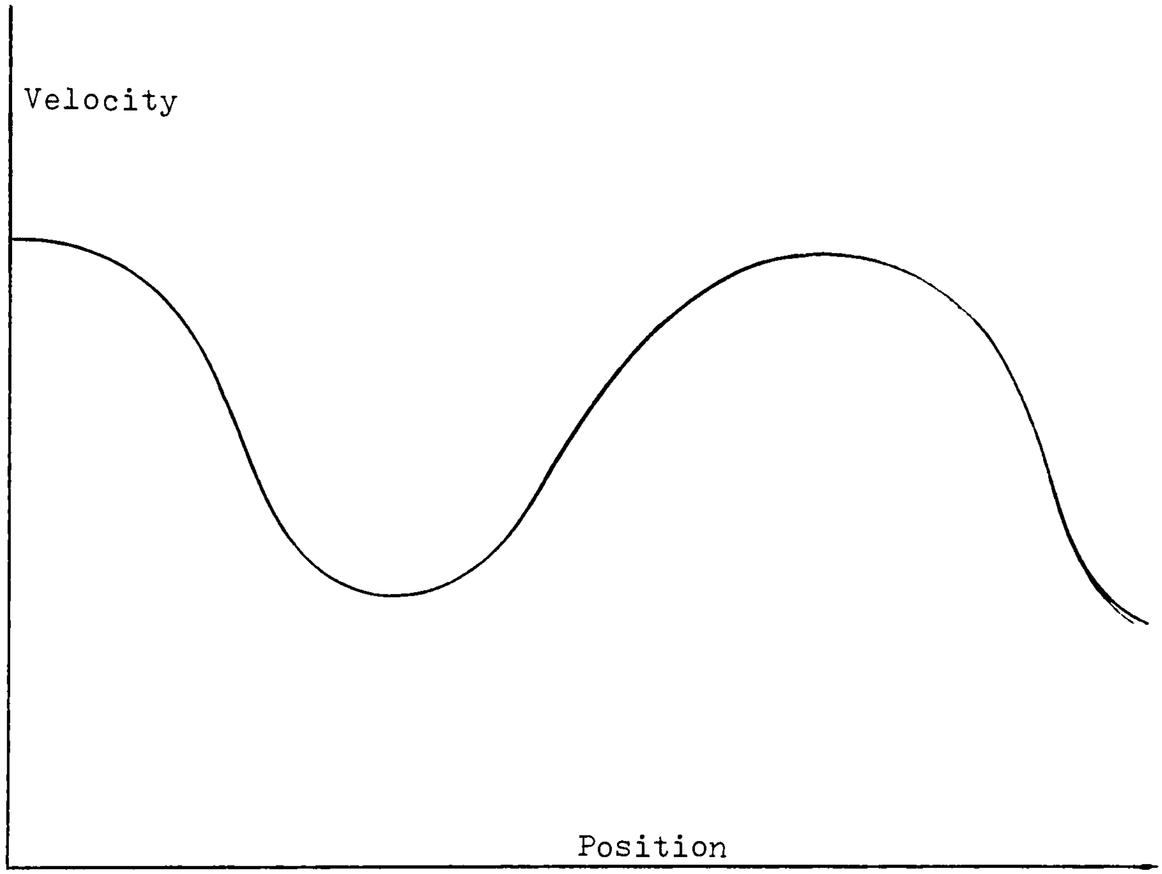

Figure 3.
Pulse Velocity verse Position

It was here that the experiment was focused. The hypothesis tested was that the velocity of an ultrasonic pulse is independent of the number of opposing waves it encounters while traveling through an acoustic medium.

The hypothesis is designed so that a rejection of the hypothesis would imply the measurement results would support the further pursuit of an eventual theory. Failing to reject implies the results do not agree with the hypothesis and the hypothesis should be modified or discarded.

II. EXPERIMENTAL

A. EQUIPMENT

In order to measure the effect of pulse velocity as a function of the number of waves passing through an ultrasonic pulse an apparatus had to be set up to measure pulse time response as precisely as possible and generate a large number of acoustic waves in the medium. The apparatus consisted of an electronic function generator, an ultrasonic analyzer, an ultrasonic transducer, and a pair of oscilloscopes. The equipment was assembled as shown in Figure 4.

1. FUNCTION GENERATOR

A Hewlett Packard model 3312A function generator contains two separate function generators, a main generator and a modulation generator. Only the main generator was used in the experiment. The frequency of the main generator is variable from 0.1Hz to 13MHz in eight decade ranges. The main generator was used to produce square wave output. The symmetry of the waveforms was varied to produce 20:80 waves.

The main generator has two outputs: a main signal output and a synchronized output. The main signal output was the modified square wave to the ultrasonic analyzer. The synchronized output provided a pulse which synchronized the oscilloscopes. The output of the main generator was

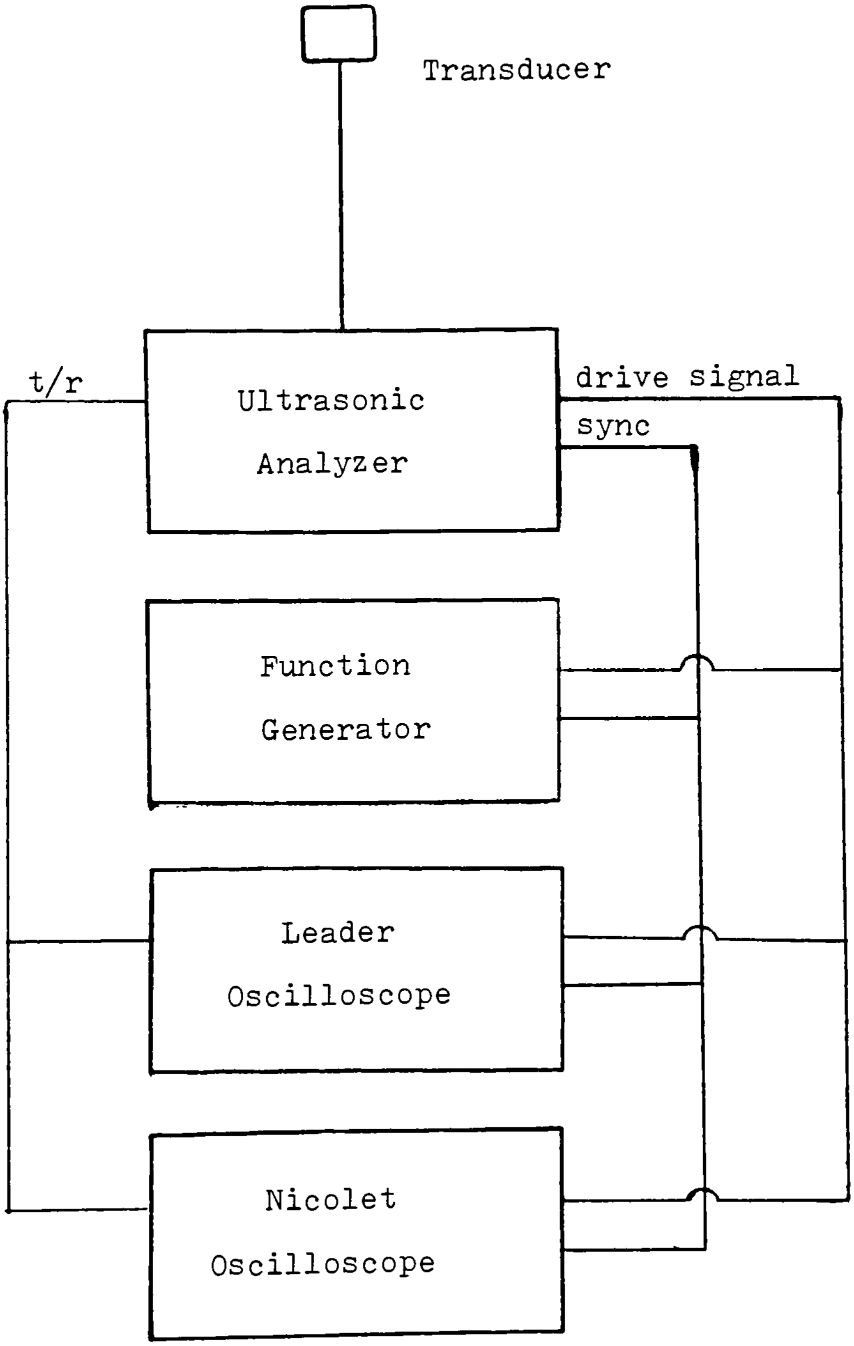

Figure 4.

Equipment Configureation

dc coupled to supply both ac and dc components of the output waveform. The sync output supplied a one volt rectangular wave which was 180 degrees out of phase with the main generator signal. The frequency and duty cycle of this pulse varied with the main output signal.

2. ULTRASONIC ANALYZER

A Panametrics ultrasonic analyzer, UA, model 5052UA, acted as an electronic switch board. It was triggered by the main generator, and produced a signal that was sent to the transducer. The ultrasonic analyzer received the returning signal from the transducer, and sent the transducer response to the oscilloscopes.

The UA is a broad band ultrasonic analyzer which includes a pulser-receiver, stepless gate, and a gated peak detector. The pulser-receiver section has discrete calibrated settings which allow the pulser-receiver related parameters to be reproduced. The pulser section of the UA was replaced by the function generator to produce short, large amplitude electronic pulses of controlled energy. When the pulses were applied to an ultrasonic transducer, they were converted into short ultrasonic pulses. The ultrasonic pulses were received by the transmitting transducer after partial or total reflection.

The voltage signals produced by the transducer, which represent the received ultrasonic pulses, were amplified by the receiver section of the UA.

a. ENERGY

The amount of pulse energy available to the transducer is controlled by the energy switch. The effect of this control is to vary the main bang pulse width as well as the main bang amplitude. The energy setting was always set to 4, maximum energy and maximum width to disturb the medium as much as possible.

b. DAMPING

There are four calibrated damping resistances across the transducer connector. The additional resistance damps the higher order oscillations of the transducer from the main bang. The damping switch was set at the maximum of 500 ohms due to the shape of the D square wave generated by the function generator.

c. HIGH PASS FILTER

The UA's high pass filter has five low frequency cutoff points (1kHz, 30kHz, 100kHz, 300kHz, or 1MHz). Since measurements were never made over 100kHz, 30kHz was the maximum low frequency cutoff.

d. T/R

The transmitter-receiver section uses the main bang pulse to drive the transducer. It also receives the transducer signal from the ultrasonic echo. This transducer response is amplified and sent to the output section of the UA, which sends the signal to the oscilloscopes.

2. TRANSDUCER

A Panameterics submersible transducer, part number 307, was used in a ten gallon tank. Since there was only one transducer, it was working in pulse echo mode where it sends and receives all of the ultrasonic energy.

The Panameterics is a Barium Titanate ceramic transducer that operates on the piezoelectric effect. The piezoelectric effect is the generation of electric polarity due to changes in pressure, especially in quartz, tourmaline crystals, and polycrystalline barium titanate ceramics<16>. The piezoelectric effect was discovered by Jacques and Pierre Curie in 1880. The amplitude and sign of the charge are directly proportional to the pressure and direction of application. The process is also reversible where the application of an electric field causes a deformation of the crystal. This reversibility allows one transducer to both transmit and receive ultrasonic pulses and responses.

3. OSCILLOSCOPES

a. LEADER

The first oscilloscope was a Leader, model LBO-522, 20MHz, dual trace oscilloscope. It was used for only reference of the main generator trigger pulse and the transducer response. This oscilloscope did not have the flexibility to perform the temporal measurements, however, it did provide a large overall picture of what the waveforms looked like when it was used at longer sweep times.

Its functions included 500uV/division at 5MHz with a maximum sweep ratio of 40ns/division, with 10 divisions. Therefore, at the fastest sweep rate, which is necessary to observe the effect of time delay, the Leader only provides 400 ns of signal information. This is much signal information is only enough for near-fields of up to 0.6mm, which is quite shallow.

Set up for the Leader was: the transducer response from the UA output section was sent to channel 1, and the main generator signal input to channel 2. The function generator synchronization signal was sent to the external trigger connector. Analog oscilloscopes control the display tube directly from the amplified signal voltages and a sawtooth sweep voltage.

b. NICOLET

The Nicolet series 2090, 20MHz, digital oscilloscope, model 206, was used to measure the temporal response of the ultrasonic pulses. The method of how a digital oscilloscope operates differs radically from that used in an analog oscilloscope. How the Nicolet oscilloscope is the signal information is converted to digital form, stored in a buffer memory, then transfered to the mainframe memory for display purposes. A microprocessor controls the beam of the display CRT. The Nicolet sweeps the signal in similar fashion as an analog oscilloscope. When the external trigger sweep signal is received, the analog-to-digital converter measures the signal at intervals separated by amounts which depend on the selected sampling rate. The A/D then transfers the information to the buffer memory. Each sweep samples 4,096 measurements. The information is then transfered from the buffer memory to the mainframe memory and the oscilloscope is ready to receive the next sweep trigger signal.

The microprocessor continually interrogates the mainframe memory and produces the waveform display as well as marker lines and numerics.

The Nicolet has a maximum sweep ratio of 50ns/point with 4,096 sampling points. This provides 0.205 milliseconds of signal information which can be expanded up to 64X on the CRT. Working with a pulse velocity of 1460m/s and 0.205 milliseconds of stored signal information, ultrasonic responses up to 30cm away can be recorded. 30cm is well into the far-field region,which is where we are interested.

With the Nicolet synchronized to the function generator, and the transducer response from the output connector of the ultrasonic analyzer in channel 1, the transducer response as a function of time can be measured. Two values are displayed in the Nicolet window. They are with reference to the position of the vertical cursor and are the relative time from the last sync pulse, and voltage. The cursor can sweep across a waveform and one can determine the time delay from the main bang, which fired a pulse from the transducer to the ultrasonic pulse ringing on the transducer. The ultrasonic pulse is represented by voltage fluctuations on the oscilloscope. By placing the vertical cursor on the peak of the pulse, one may measure the travel time of the pulse to within ± 0.5us.

B. DATA COLLECTION

The temporal response of the transducer was measured in a straight forward manner using simple physical relationships and the Nicolet oscilloscope. To determine what ring on the oscilloscope was the pulse being measured, the following equation was used.

$$t = 2D/V \qquad (2)$$

Temporal measurements were made from peak to peak voltages of the driving pulse and the first echo using the Nicloet oscilloscope. To determine the frequency which generated a specific number of opposing waves at that depth, and one transducer, divide the number of waves by the pulse travel time, equation (3).

$$f = W/t \quad (3)$$

Since there are physical limitations to the equipment, there was a maximum number of opposing waves that could impede the pulse. The most important limitation was that there was only one transducer element available. Other limitations were that frequencies over 100kHz resulted in aliasing on the Nicolet, and the tank was only 25cm deep. Using these parameters, the maximum number of waves was 33. One possible way to increase the number of waves in the medium, was to use an array of transducer elements rather than just one. The number of waves increases as a multiple of the number of transducer elements. Unfortunately, there was not a transducer array available for research that was compatible with the rest of the equipment. The solution that was used to generate more waves was an array simulator using parallel reflecting plates and standing waves.

Acoustic standing waves can be setup in noncompressible media. Water will undergo longitudinal vibrations when acousticly excited. Standing longitudinal waves can be set up in a tank of water

C. TRANSDUCER ARRAY SIMULATOR

An ultrasonic transducer array simulator was constructed from two (18x35x0.4)cm aluminum plates, four 9 inch sections of 3/16 threaded rod, and 16 sets of hex nuts, locks, and flat washers, see figure 5.

Consider two waveforms with the same amplitude, frequency, and wavelength, but traveling in opposite directions. Waveform such as the transmitted and the reflected waves in figure 2. From the superposition principle, the algebraic sum of the wave forms results in

$$y = (2Y\sin kx)\cos wt \quad (4)$$

Equation (4) represents the wave form of a standing wave. Since the amplitude of the standing wave at any value of x is equal to $2Y\sin kx$, the maximum amplitude has the value 2Y This occurs when the x position satisfies the condition $\sin kx = 1$.

$$kx = \pi/2,\ 3\pi/2,\ 5\pi/2, \ldots \quad (5)$$

Getting back to the transducer in the tank, standing waves are set up in the tank by a continuous superposition of waves reflected off the bottom and transmitted from the transducer. Each depth has a number of natural patterns

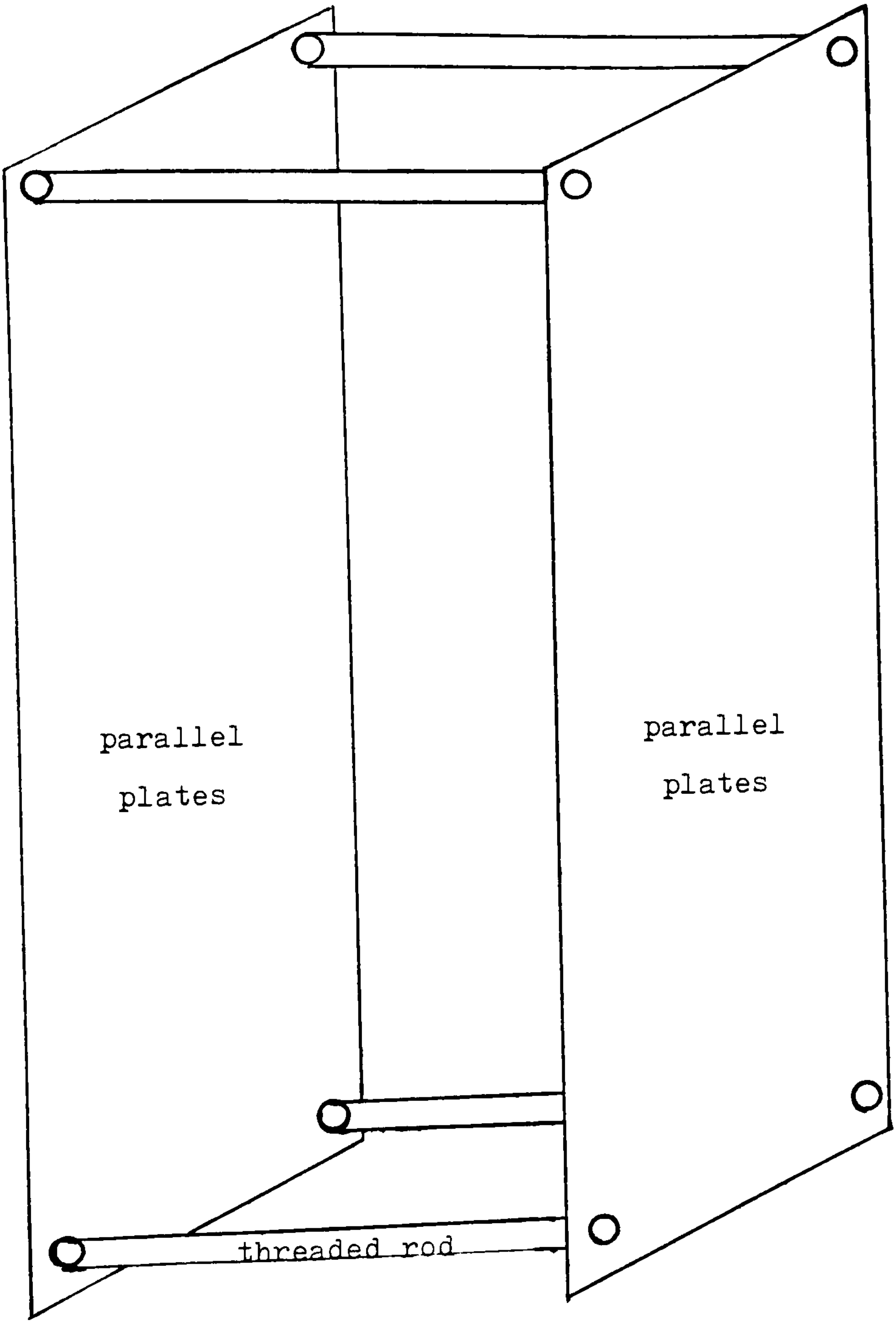

Figure 5.

Transducer Array Simulator

of oscillations, called normal modes. Each mode has a characteristic frequency. To calculate the characteristic frequency, we start with the depth of the transducer equal to $\lambda/4$, see figure 6. From (5) the characteristic frequency is

$$f = V/4D \quad (6)$$

Since the bottom of the tank is a displacement node, only the odd overtones are present.

$$fn = nV/4D \quad (7)$$

The resulting standing waves produce all the apparent opposing waves for the measured ultrasonic pulse to pass through as though there were n transducers. The simulated array elements all fire in phase, and are completely electrically uncoupled. The ultrasonic transducer array simulator was constructed at a cost of $1.49 in hardware.

On 3-29-85, the location of the investigation was moved from 08-3109 to 08-A321 in the Carson building at RIT. The ambient room temperature of 08-A321 was 3.8C less than in 08-3109. The speed of sound is dependent on the temperature of the medium, and this change in temperature resulted in two independent sets of data.

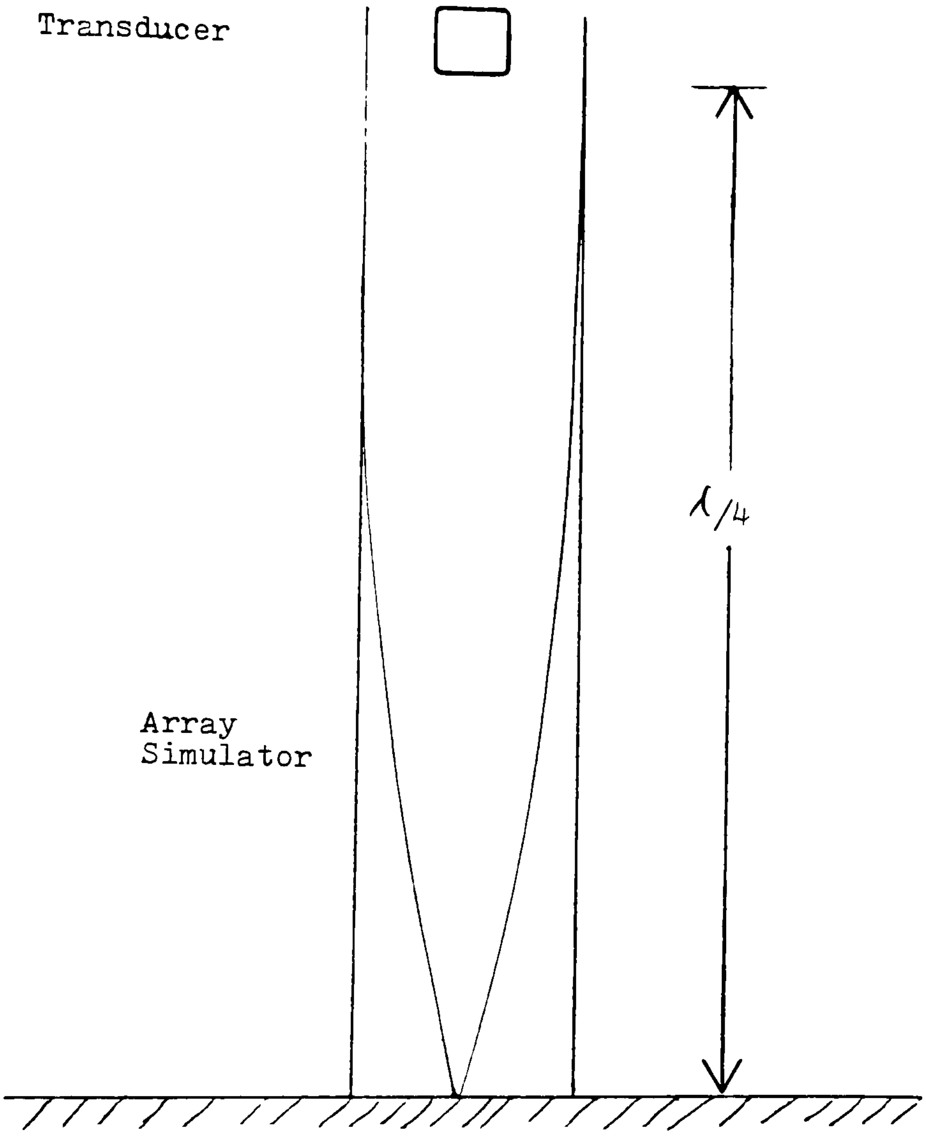

Figure 6.

First Harmonic of a Standing Longitudinal Wave

III RESULTS

Table 1.

Pulse Velocity as a Function of Waves, Temp 1.

NUM OF WAVES	kHz	EFFECTIVE ELEMENTS	DEPTHm	TIMEus	PULSE VELOCITYm/s
0.5	2.273	1	0.160	219.8	1454
0.5	1.280	1	0.283	390.5	1449
0.5	1.317	1	0.276	379.6	1454
0.5	1.429	1	0.255	349.7	1458
0.5	1.511	1	0.240	330.5	1450
0.5	1.657	1	0.220	301.5	1458
220	65.52	21	0.117	162.3	1460
220	47.73	21	0.160	219.9	1454
220	30.02	21	0.255	349.7	1458
220	31.73	21	0.240	330.5	1450
220	33.54	21	0.228	313.9	1456
480	70.46	31	0.160	219.9	1454
480	39.69	31	0.283	390.8	1449
480	40.83	31	0.276	379.8	1454
480	44.32	31	0.255	349.7	1458
480	46.84	31	0.240	330.5	1450
544	43.461	33	0.276	379.8	1454
544	47.18	33	0.255	349.7	1458
544	49.86	33	0.240	330.5	1450
544	49.50	31	0.228	313.9	1456

Table 1, continued

544	51.36	31	0.220	301.5	1458
544	42.25	33	0.283	390.8	1449
612	44.81	35	0.283	390.8	1449
612	46.09	35	0.276	379.8	1454
612	50.04	35	0.255	349.7	1458
612	52.89	35	0.240	330.5	1450
612	54.67	33	0.220	301.5	1458
612	52.70	33	0.228	313.9	1456
684	47.37	37	0.283	390.8	1449
684	48.73	37	0.276	379.8	1454
684	52.90	37	0.255	349.7	1458
684	57.98	35	0.220	301.5	1458
684	55.90	35	0.240	330.5	1450
684	55.89	35	0.228	313.9	1456
760	49.93	39	0.283	390.8	1449
760	51.36	39	0.276	379.8	1454
760	55.76	39	0.255	349.7	1458
760	58.93	39	0.240	330.5	1450
760	59.09	37	0.228	313.9	1456
760	61.30	37	0.220	301.5	1458
840	52.49	41	0.283	390.8	1449
840	54.00	41	0.276	379.8	1454
840	58.62	41	0.255	349.7	1458
840	61.95	41	0.240	330.5	1450
840	62.28	39	0.228	313.9	1456

Table 1, continued

840	61.41	39	0.220	301.5	1458
924	55.05	43	0.283	390.8	1449
924	56.63	43	0.276	379.8	1454
924	61.48	43	0.255	349.7	1458
924	64.97	43	0.240	330.5	1450
924	65,47	41	0.228	313.9	1456
924	67.93	41	0.220	301.5	1458
1012	57.61	45	0.283	390.8	1449
1012	59.26	45	0.276	379.8	1454
1012	64.34	45	0.255	349.7	1458
1012	67.99	45	0.240	330.5	1450
1012	68.67	43	0.228	313.9	1456
1012	71.24	43	0.220	301.5	1458
1104	60.17	47	0.283	390.8	1449
1104	61.90	47	0.276	379.8	1454
1104	67.20	47	0.255	349.7	1458
1104	71.86	45	0.228	313.9	1456
1104	74.55	45	0.220	301.5	1458
1200	62.73	49	0.283	390.8	1449
1200	64.53	49	0.276	379.8	1454
1200	70.06	49	0.255	349.7	1458
1200	75.05	47	0.228	313.9	1456
1200	77.87	47	0.220	301.5	1458
1300	65.29	51	0.283	390.8	1449
1300	67.17	51	0.276	379.8	1454

Table 1, continued

1300	72.91	51	0.255	349.7	1458
1300	78.25	49	0.228	313.9	1456
1300	81.18	49	0.220	301.5	1458
1404	67.85	53	0.283	390.8	1449
1404	69.80	53	0.276	379.8	1454

Table 2.

Pulse Velocity as a Function of Waves, Temp 2.

NUM OF WAVES	kHz	ELEMENTS	EFFECTIVE DEPTHm	TIMEus	PULSE VELOCITYm/s
0.5	0.68	1	0.253	343.1	1475
0.5	2.03	1	0.183	245.6	1488
0.5	1.62	1	0.223	300.9	1480
0.5	1.88	1	0.197	265.7	1483
0.5	2.40	1	0.153	205.8	1488
0.5	3.12	1	0.117	160.7	1460
1.5	5.64	1	0.197	265.7	1483
1.5	7.19	1	0.153	205.8	1488
1.5	9.36	1	0.117	160.7	1460
1.5	4.37	1	0.253	343.1	1475
1.5	6.09	1	0.183	245.6	1488
1.5	4.87	1	0.223	300.9	1480
5	18.79	1	0.197	265.7	1480
5	0.39	1	0.253	343.0	1475
5	20.33	1	0.183	245.5	1488
5	16.23	1	0.223	300.9	1480
5	9.36	1	0.117	161.5	1460
15	38.7	1	0.212	284.3	1477
15	43.73	1	0.253	343.1	1475
15	60.98	1	0.183	245.5	1488
15	48.70	1	0.223	300.9	1480
15	56.39	1	0.197	265.7	1480

Table 2, continued

15	71.91	1	0.153	205.7	1488
15	15.63	1	0.117	161.5	1460
25	72.89	1	0.253	343.1	1475
25	87.94	1	0.212	284.3	1477
25	101.64	1	0.183	245.5	1488
25	93.98	1	0.197	265.7	1480
25	119.87	1	0.153	205.7	1488
25	21.84	7	0.117	161.5	1460

The statistic used to test the hypothesis was a two-sided alternative hypothesis test<17>. Velocities of the pulse in higher wave count situations were compared to the velocity of the ultrasonic pulse when there were no opposing waves present. A 95% critical region was generated around the mean velocity with no opposing using a student-t distribution and the confidence equation

$$|v-u.| \geq (tv,alpha/2)(s/\sqrt{n}) \quad (8)$$

For the two temperatures,

$$(tv,alpha/2)(s/\sqrt{n}) = 3.65$$

v = 10

alpha = 0.025

n = 11

T = 20.5C

$$(tv,alpha/2)(s/\sqrt{n}) = 2.89$$

v = 7

alpha = 0.025

s = 3.46

n = 8

T = 24.3C

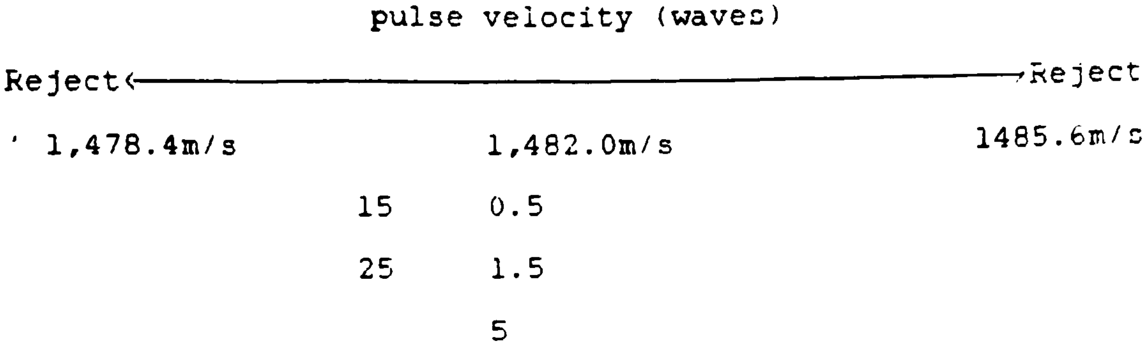

Figure 7.

Critical Region For Alternate Hypothesis Test, T = 20.5C pulse velocity (waves)

Reject ←——————————————————→ Reject

1,451.7m/s 1,454.6m/s 1457.5m/s

480 0.5 220

544

612

684

760

840

924

1012

1104

1200

1300

Figure 8.

Critical Region For Alternate Hypothesis Test, T = 24.3C

IV DISCUSSION

The technique used to measure pulse velocity is one of the fundamental applications of ultrasonics. Its validity is unquestionalbe and the present ultrasonic industry was built around it. An ultrasonic pulse travels through a homogenous medium at a constant rate. In this investigation, the medium density was varied using the actual ultrasonic pulses. This was the justification for the research: what happens when the medium is altered by thousands of ultrasonic disturbances.

the temporal response of an ultrasonic transducer was measured in a number of different circumstances. Ultrasonic velocities were measured at different frequencies, with single and simulated multiple transducer elements, and at different depths. The number of ~~transducers~~ [illegible] waves did not effect the velocity of the ultrasonic pulses. That is to say, none of the situations measured here rejected the hypothesis. Since the results disagree with the postulate, modification of the hypothesis is necessary.

To describe what happened consider wave patterns generated in the system. As each compression wave travels through the medium it increases the pressure and the density of the regions it passes. The increase in density would decrease the velocity. This was the basis of the hypothesis. What was observed was that pulse velocity did not change as a function of the number of opposing waves. An explanation of this is that traveling right behind the high density wave is a low density region known as a rarefraction.

The transducer oscillates back and forth, and regions of compression and rarefraction are continuously set up. As the regions travel through the array simulator, the variation of the medium is given by

$$dp = P\sin(kx-wt) \quad (9)$$

The velocity is therefore not constant, but a function of position, time, wavelength, and angular frequency of the transducer. The low density rarefractions were not included in the hypothesis. Rarefractrions decrease the pulse velocity. Including rarefractions in the hypothesis describes the velocity the velocity of ultrasonic pulses passing through a high frequency, multi-element, disturbed medium. Pulse velocity is impeded by opposing waves, however, it is also accelerated through the low density rarefractions for each wave. Pulse velocity is not constant, it deccelerates and accelerates every time the pulse travels through a wave. The resulting average pulse velocity is constant, as measured here. Acoustic cross-coupling is not due to the presence of opposing waves in the medium. Indeed, modification of the hypothesis would make it agree with classical physical relationships<18>.

There are some proposed ways to measure acoustic cross-coupling<19>. A convenient method is to place a small probe in contact with the transducer array directly in front of the 0'th element. A drive signal is then applied to the n'th element sequentially by a switch, starting with the 0'th element, then the first, second, and so forth. The signal received on the probe is amplified by the UA and sent to an oscilloscope.

By switching the drive signal from one element to the next, the small probe remains in a fixed position and the coupling to the array is not disturbed or altered. Therefore, the relative strength of the received signal, which arises due to acoustic waves propagating along the array, is a measure of the cross-coupling. By normalizing to the received signal when element 0 is driven, the absolute magnitude of the cross-coupling can be determined.

V CONCLUSIONS

Even though the number of waves the ultrasonic pulse passed through was varied by three orders of magnitude, there was no change in pulse velocity. The hypothesis could not be rejected for any of the opposing wave situations tested. Therefore, we fail to reject the original hypothesis that the velocity of an ultrasonic pulse is independent of the number of opposing waves it encounters while traveling through an acoustic medium.

Further research would include photographing an actual ultrasonic pulse in an acoustic medium. A possible technique for capturing such a shot would involve a high energy ultrasonic transducer with low acoustic impedance, a water tank with optical quality sides, a very fast stroboscope. frequency control over the ultrasonic system, a Schlieren Z optical system, a large format camera, and quite possibly, digital image processing. Figure 9 shows a possible configuration.

The Schlieren Z system uses a set up of symmetrical, front-silvered, mirrors, a point source, a slit aperture, and a knife edge. The stroboscope would be used as the light source. The slit is placed, off axis, at the focal length of the first mirror, ml. The light coming from ml is parallel and goes through the wave tank, falls at an off axis mirror, m2. The reflected light from m2 is focused on

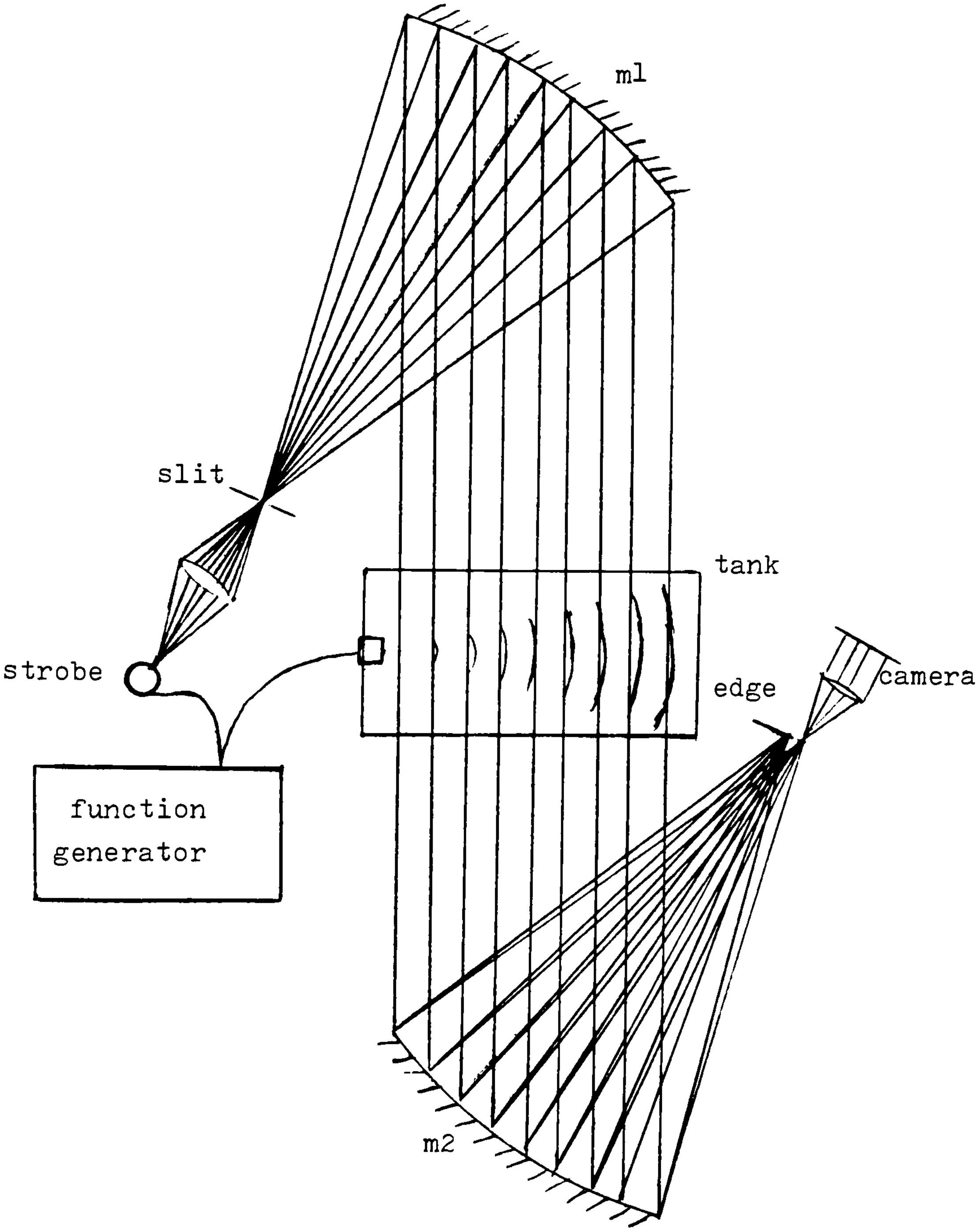

Figure 9.

Schlieren Optics and Ultrasonic Equipment the knife edge, which is parallel to the slit. The knife edge is moved into the diffraction image plane by means of a micrometer. As the knife edge crosses the central intense section of the diffraction pattern, the lower half of the pattern is blocked off from the camera. Just before the knife edge covers the central maximum, the field becomes visible. Phase changes between higher orders of interference on one side produce constructive and destructive interference patterns<20>.

The ultrasonic set up would be the same as in the temporal response measurements as shown in figure 4. The stroboscope would be synchronized, with a delay, to the function generator. In order to capture one pulse, the strobe would need a flash duration of approximatly 1/150,000 second. Another possible way to photograph a pulse,using the same system, is to set up standing waves and determine if an image can be generated on the focal plane of the camera by using continuous light and adjusting the frequency of the transducer. Preliminary attempts at using this technique were unsuccessful.

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