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A SEMI-AUTOMATED PULSE-ECHO ULTRASONIC SYSTEM FOR INSPECTING TIRES

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16. Abstract

A nondestructive tire-testing system has been developed using the pulse-echo ultrasonic technique, which offers substantial advantages over all other physical nondestructive-testing methods and shows promise of reducing the cost of production-tire inspection.

Developed under the sponsorship of the National Highway Traffic Safety Administration NHTSA (M.J. Lourenco, Program Director), the system was specifically designed to meet the requirements for detecting flaws in new tires. For this application, the reliable detection of possibly subtle flaws demands sophisticated techniques, but costs can be minimal because a high level of automation may be used.

Work is underway to relate tire failure to anomalies observable by reflection ultrasonics. If satisfactory correlation can be demonstrated, the system may be used to screen larger samples of tires before testing for compliance with Motor Vehicle Standard 109.

This report describes the ultrasonic techniques, explains the operation of the system and presents examples of data displays produced by the system test results from a small sample of tires.

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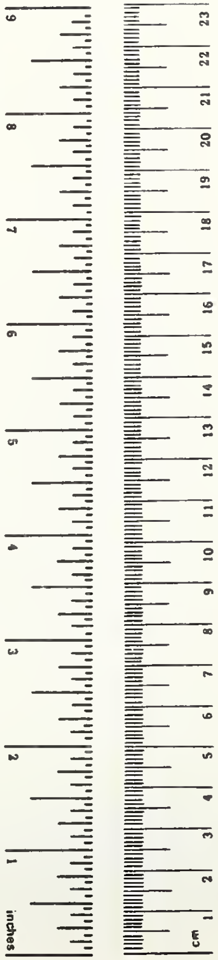
PREFACE

The equipment described herein was developed as a part of the nondestructive tire-testing program carried on at Transportation Systems Center. The machine was built under contract by Teknekron, Inc., of Berkeley, California in accordance with specific system concepts and performance specifications developed in preliminary work at Transportation Systems Center by Robert P. Ryan. Mechanical systems were subcontracted to RF Systems, of Cohassett, Massachusetts. The work has been sponsored by the U.S. Department of Transportation, National Highway Traffic Safety Administration, Manuel J. Lourenco, Program Director.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

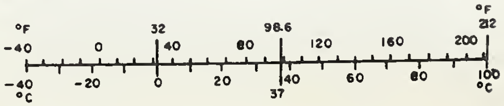


TABLE OF CONTENTS

Section Page

ILLUSTRATIONS

1. INTRODUCTION

The U.S. Department of Transportation, Transportation Systems Center in Cambridge, Massachusetts, under the sponsorship of the National Highway Traffic Safety Administration, has had a program for developing a reliable and economical means for finding flaws in tires and relating these flaws to service failure. Pulse-echo ultra-sonics is the only physical technology that shows promise of finding most defects which can impair the safety of a tire. Therefore, a development program was started which was to reduce to practice the concept of complete tire inspection by ultrasound.

A breadboard model was first developed to prove the feasibility of using liquid-coupled ultrasonics on a tire. This is described elsewhere, see (Ryan, R.P., Feasibility of High-Resolution Pulse-Echo Techniques for Automobile Tire Inspection, HS-801067, PB-231-201, DOT-TSC-NHTSA-72-11, June 1973). With feasibility established, what was left was the development of a prototype capable of demonstrating the ability to completely inspect tires at practical rates of speed with readily understandable results. This report describes the results of that development.

2. SYSTEM DESCRIPTION, GENERAL

A general overview of the tire-handling part of the tire-testing machine is shown in figure 1. This tire handler is an immersion system with a large tank about 4 feet deep. Total immersion rather than partial immersion is used to aviod any possibility of difficulties which could be caused by immersion; i.e., the reflection of the ultrasound by air bubbles as the tire rotates for scanning.

As shown in figure 2, the tire is mounted on a split rim and inflated with the aid of a pneumatic cylinder device which removes and installs the outer half of the rim. The rim-halves are held together against the outward thrust of the inflation pressure by a heavy bayonet latch inside of the tire. The cylinder thrusts toward the tire, grips the outer rim-half (which is made of steel and is nickle-plated) with a group of electromagnets, and holds it while the tire-scan motor rotates the stub shaft 45 degrees to unlock the bayonet latch. The air cylinder is then retracted to permit removal and replacement of the tire, and the process is reversed. The tire is inflated and deflated through the shaft assembly.

There are three such split-rim tire stations on the ends of the three arms of a large spider or vertical carousel. Whenever one arm is at the load/unload position, the other two stations are totally submerged, one at a debubbling position, the other at an inspection position. Once a tire has been mounted, it is moved to the debubbling station by a 120 degree rotation of the spider, driven by a 1-horsepower cam-actuated Ferguson index drive, shown in figure 3. At the same time, the previously debubbled tire is carried to the inspection station, and the previously inspected tire is brought to the unload/load station.

As shown in figure 4, a set of transducers is arranged in a ring around the cross section of the tire. The transducers are pulsed in sequence, and the returning echo signals are processed in sequence with the air of electronic-switching. Thus, the entire

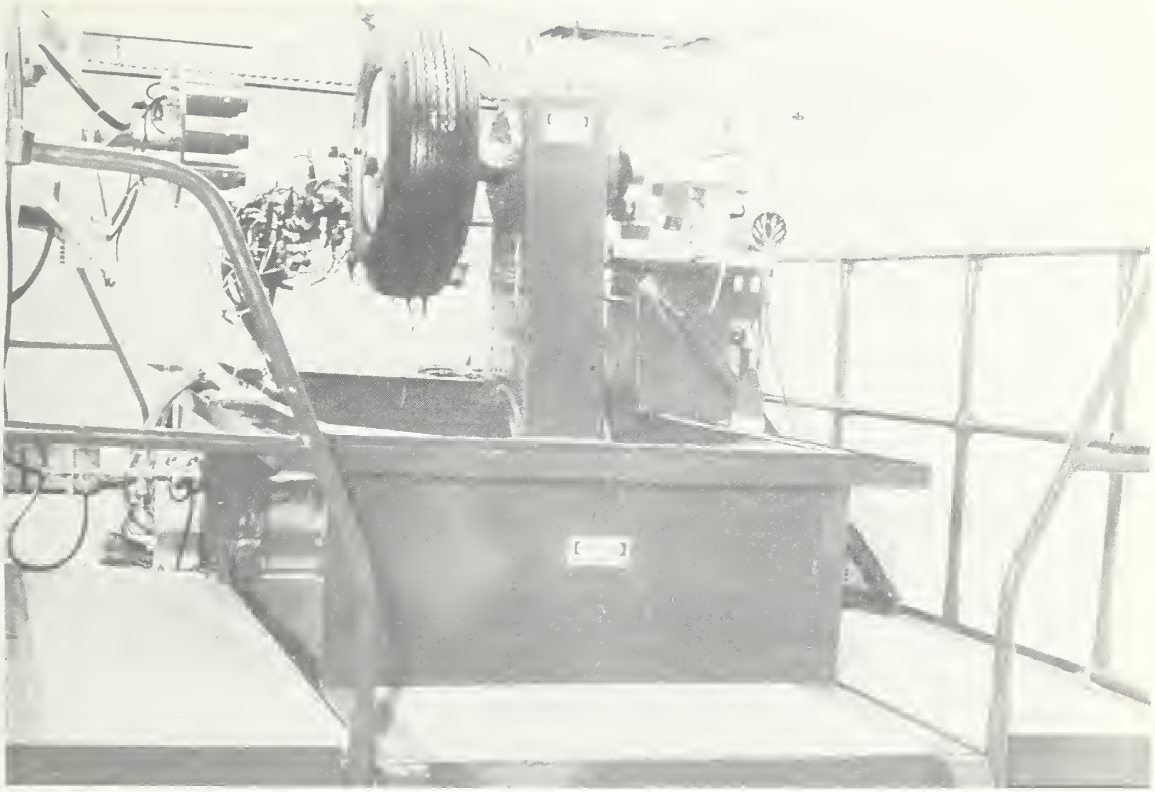


FIGURE 1. OVERVIEW OF TIRE HANDLER
A Three-Station Vertical Carousel Carries Tires From The Unload/Load Station Shown To A Debubble Station And An Inspection Station. The Tire Is Totally Submerged For Debubbling And Inspection To Avoid Entrainment Of Surface Air Bubbles.

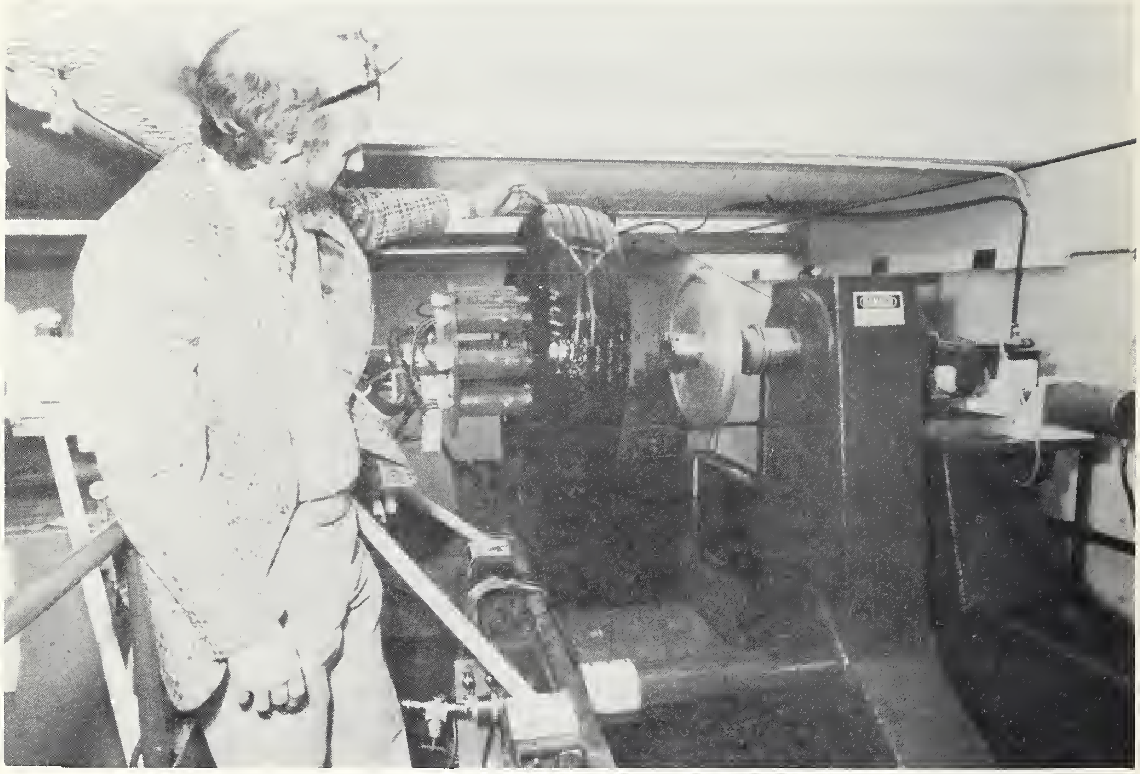


FIGURE 2. TIRE LOADING
Outer Rim-Half Is Gripped By Electromagnets And Removed By A Pneumatic Cylinder. Outward Thrust Of Inflation Pressure Is Supported By An Internal Bayonet Latch Which Is Rotated For Engagement And Disengagement By The Tire-Scan Stepping Motor.

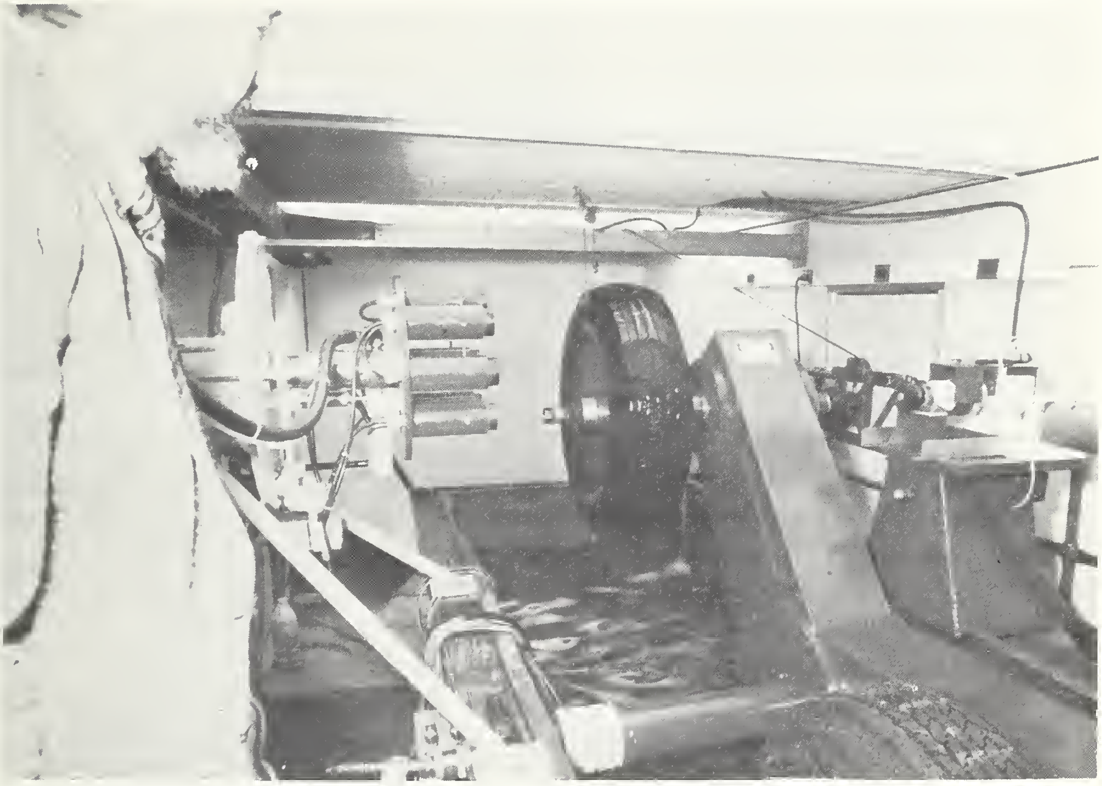


FIGURE 3. INDEXING OF SPIDER
One-Hundred Twenty-Degree Rotation Advances Tires From Load/Unload Station And Debubble And Inspection Stations

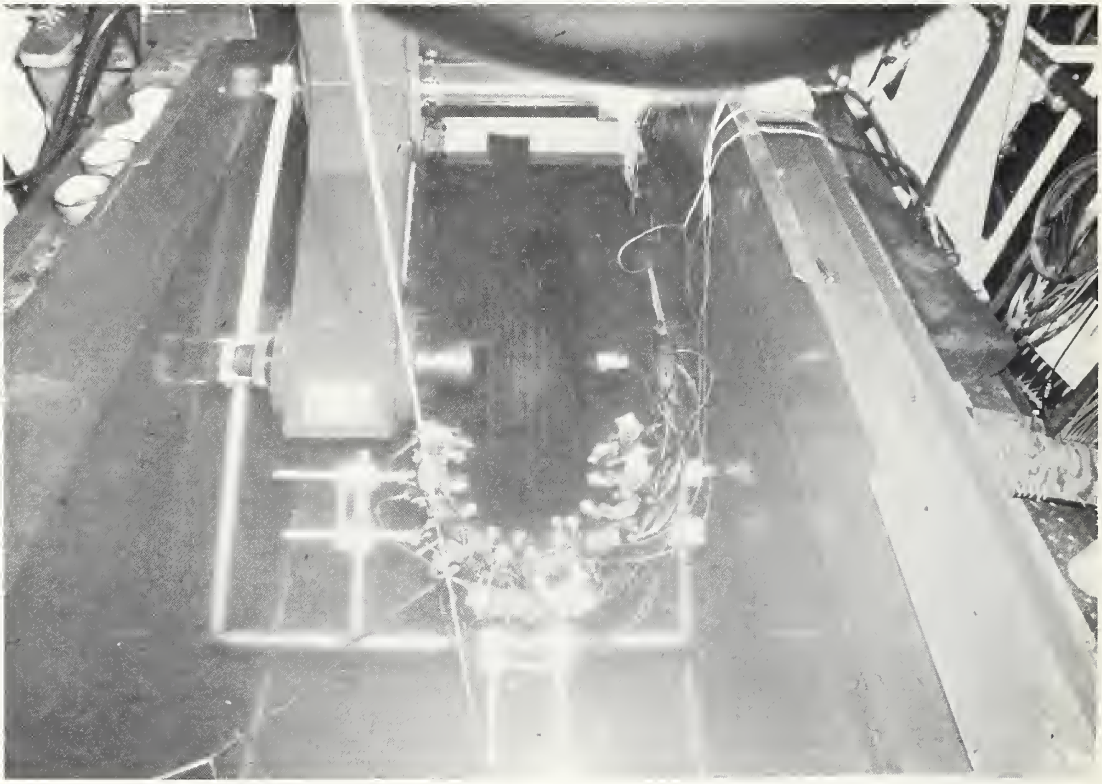


FIGURE 4. TRANSDUCERS IN WORKING POSITION

surface of the tire is scanned during a single revolution. Sequenced at a rate of 2.4 kilohertz, each of the transducers (24 in number) is pulsed 1000 times during the 10-second scan, so that the tire is examined at 24,000 spots on its surface.

The Ferguson drive can index the spider in about 2 seconds. The actual ultrasonic-scanning can also be accomplished within about 2 seconds. Theoretically, a throughput of 4 to 6 tires per minute could be obtained. At the present stage of development, however, the index time is slowed down to about 5 seconds to avoid excessive splash. The tire-mounting cycle is slowed to about 20 seconds for operator safety. While one tire is being scanned, the next tire is being debubbled by a set of high-velocity water jets. The load/unload operation cannot be conducted simultaneously because reverse rotation is required to unlock the bayonet latch, and the three stub shafts are coupled mechanically by a roller chain drive inside of the spider and driver by a single stepping motor. Finally, the scanning time itself is stretched out to 10 seconds because of the limited power of the scanning motor. For the present system, the mechanical limit of throughput is a little better than a tire per minute.

The system operates in the pulse-echo mode; i.e., each transducer sends out a short pulse of ultrasound, lasting about 0.67 microseconds which travels through the water and into the body of the tire. Echo signals are reflected back to the same transducer from the various structural elements; e.g., belts, plies, etc., and finally, from the inner surface of the tire. The only ultrasonic limitation on scanning rate is the requirement that all of the echoes from a given pulse be received before the next pulse is sent out, and for suitable transducer-spacing from the tire, this time would be about 70 microseconds. In this case, the same data would be acquired in approximately 1.7 seconds.

3. SETUP OF TRANSDUCERS

To make the pulse-echo technique work for tires, a second special requirement, no less important than total immersion, is to have the transducers perpendicular to the layered interfaces inside of the body of the tire, so that specular reflections from the reinforcing elements can be received. To facilitate such mechanical alinement, the transducer support yoke is pivoted on sleeve bearings at the main axis of the spider, so that it can be swung up near the surface of the water as is shown in figure 5. The spider is stopped halfway in an index operation, and then, jogged and hand-cranked to bring the tire up to the surface, such that it will be in the same position relative to the transducers as in the inspection position. Thus, the coarse mechanical adjustments involving manual adjustment of clamping screws, fixtures, etc., can be reached while the transducers are totally under water, and it is possible to observe the echo signals on an oscilloscope. The criterion for proper alinement is simple; i.e., the echo signals are maximized and the layered structure is resolved to the maximum extent possible. Referencing of the transducers relative to the outer surface of the tire is not practical because the outer surface of the tire is seldom parallel to the internal layered structure of the reinforcing materials.

To make the transducer adjustment procedure as easy as possible, each transducer is mounted on a small manipulator mechanism, so designed that the various required adjustments are as nearly independent as possible. Figure 6 shows one of these manipulators and illustrates the kinematics of the design. Transducer manipulators are mounted alternately on the top and bottom sides of three arc-segment rails having an H-shaped cross section, one of which is shown.

These rails are called "ø-rails" (PHI-rails) because the position of each transducer along its supporting ø-rail corresponds to what we call the ø-coordinate, which measures angular position

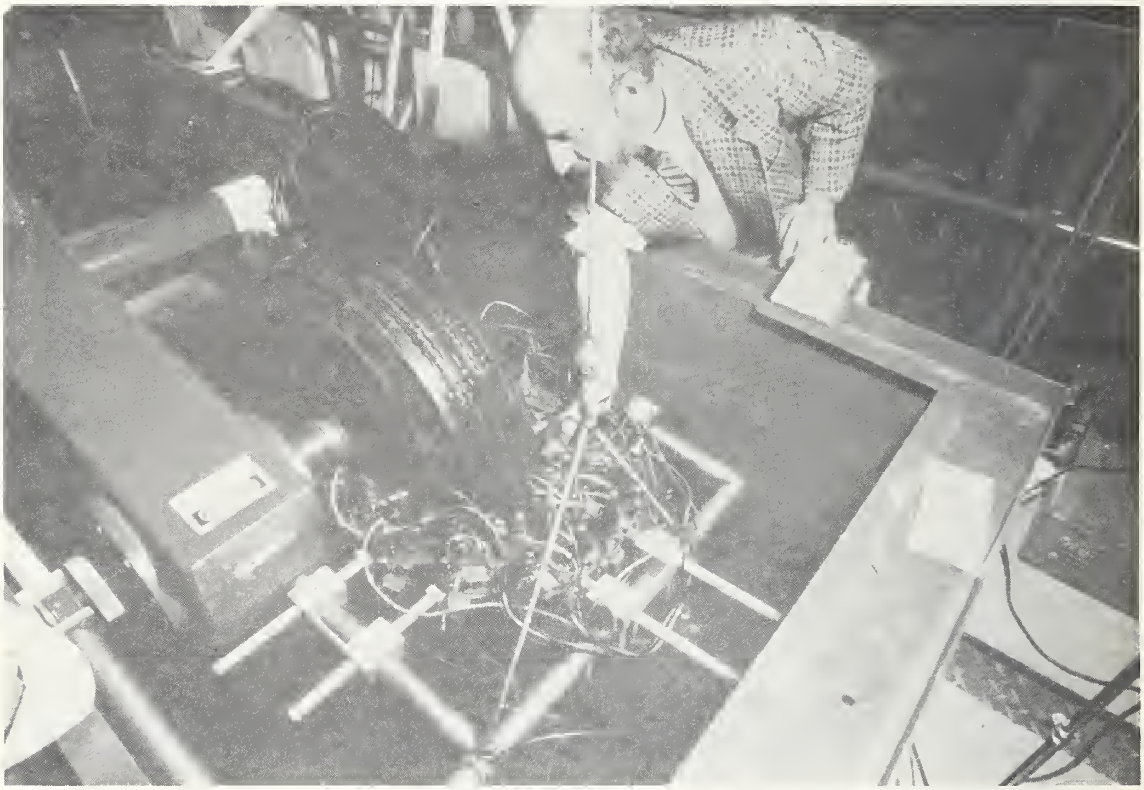


FIGURE 5. TRANSDUCERS IN POSITION OF COARSE MECHANICAL ALINEMENT

around the center of the cross section of the tire. The ϕ-angle is taken to be 0 degrees toward the wheel axle, and increases to about 90 degrees at the center of the blackwall (serial number) side, etc. The three ϕ-rail segments can be positioned independently to make their arc centers coincide approximately with the local center of curvature for the adjacent ply layers in the tread region and in each side of the tire, respectively. The normal to the tire structure then coincides approximately with a radius of the ϕ-rail, and would do so exactly if the tire shape were actually circular over the corresponding ϕ-segment.

To accommodate small departures from this ideal, a correction angle denoted by α (alpha) can be introduced by moving the transducer on a smaller arc slide, referred to hereafter as the "α-slide". Each α-slide can be positioned in or out along a radius of the ϕ-rail, so that the arc center of each α-slide lies within the tire body at the depth of the ply layer of most interest. Thus, motion along the α-slide is equivalent to rotation about the volume element of the tire being inspected, and changes in the angle of incidence in the beam can be made without changing the volume element being examined.

Finally, the transducer can be moved in and out along a radius of the α-slide to achieve the desired water path distance, and each transducer can be tilted up or down from the cross-sectional plane to make the beam axis perpendicular to the tangent plane in that direction also. At first, this design may appear to be overly complex; however, a simpler design could be much more tedious to set up because the various adjustments would be highly interacting.

For successive tires of the same design, the only adjustment which is very critical and likely to change is the α-angle. Remote adjustment of the α-angle is provided by a small stepping motor on each manipulator. This remote trimming capability permits precise reflection-amplitude measurements to be made without the results being confused by minor changes in tire shape. Coarse adjustments that have to be made manually are only required when there is an appreciable change in tire size or shape.

FIGURE 6. TRANSDUCER-MANIPULATOR KINEMATICS

4. PARAMETER ADJUSTMENT AND DISPLAY

Figure 7 shows an overview of the scan-control and data-evaluation console. At the left-side, there is a rack containing 24 pulser/receiver amplifiers, one for each of the transducers. The main rack, encircled by the operator's table, contains the control electronics and the signal-processing and display elements of the system. Lighted pushbuttons select and indicate scanning, signal-processing, and display modes. Scan-data displays are generated on a scan-converter image-memory tube and presented for evaluation on a large television monitor. Signal-processing is digitally controlled, and the scan-programmed signal processor provides up to 32 adjustable parameters which can have independent values for each of the 24 channels. A laboratory oscilloscope providing an "A-scope" presentation can be selectively triggered to monitor the effects of adjustments of the parameters for any one channel at a time. The knob panel directly in front of the operator, which is shown close up in figure 8, is effectively switched to control 18 of the available parameters for the selected channel viewed on the A-scope. Digital values corresponding to the knob settings can then be loaded into the control memory. By repeating this process for each of the channels, appropriate parameters can be loaded to suit a given size and type of tire.

To assist the operator in the managing and recording of these parameters, a minicomputer provides a tabular display of the parameter values as shown in figure 9, and permits entry or alteration of selected parameters via the keyboard, and/or re-entry of parameter sets from a digital storage medium.

Either the scan-data image-format displays from the large television monitor, or the alphanumeric parameter displays shown on the small television monitor, can be printed on paper by a video-facsimile recorder (out of view in the figures).

The video tape recorder (visible behind the operator's shoulders in Figure 7) permits the raw, unprocessed echo signals to be recorded whenever a tire is scanned. Thereafter, any of the various kinds

FIGURE 7. SCAN-CONTROL AND DATA-EVALUATION CONSOLE

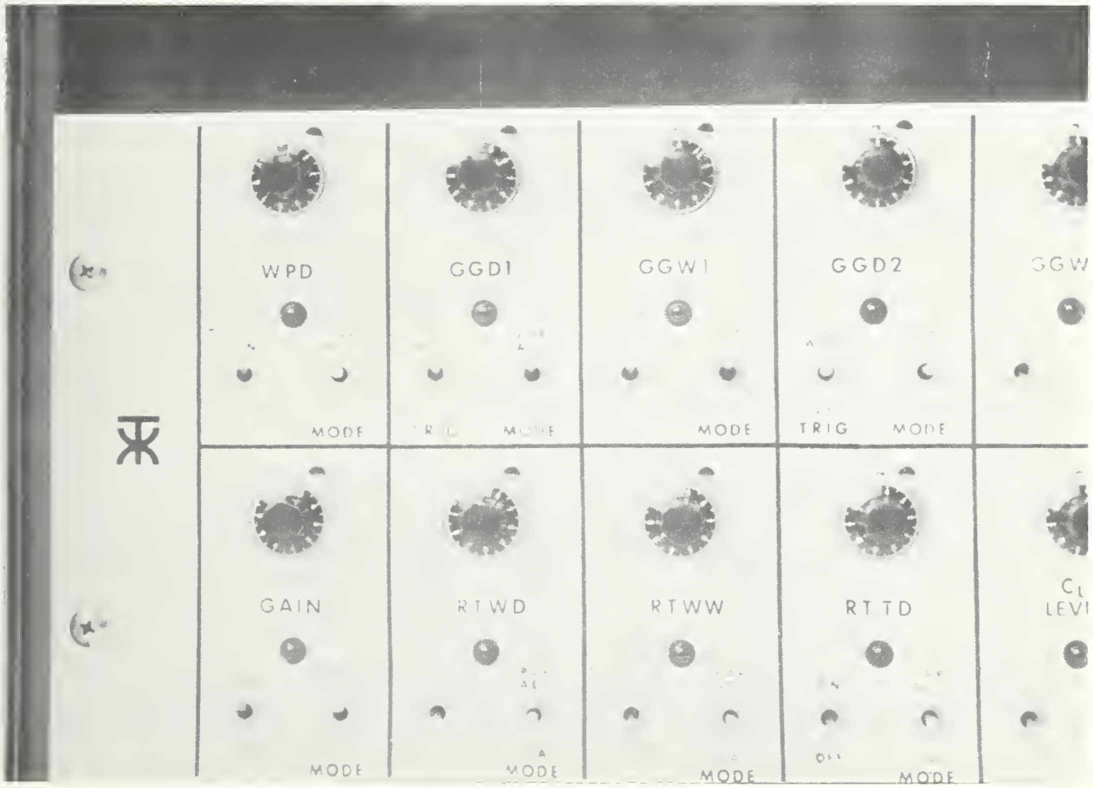
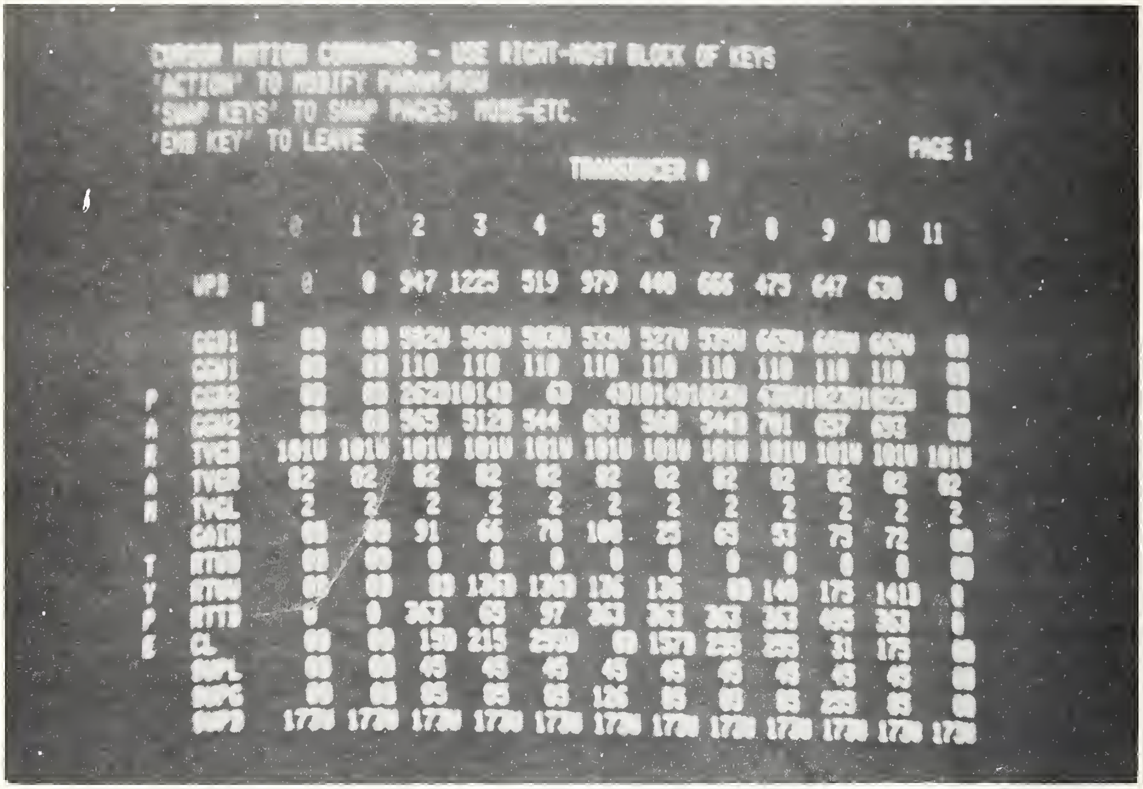


FIGURE 8. PARAMETER-ADJUSTMENT KNOBS
If Mode Switch Is At Parameter Adjust, System Uses Knob-Generated Value For Selected Transducer Instead Of Value From Parameter Memory. Load Position Puts Knob Value In Memory.



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CURSOR MOTION COMMANDS - USE RIGHT-MOST BLOCK OF KEYS
'ACTION' TO MODIFY PARAM/ROW
'SWAP KEYS' TO SWAP PAGES, MODE-ETC.
'END KEY' TO LEAVE
                                                              PAGE 1
                                  TRANSDUCER 0

              0     1     2     3     4     5     6     7     8     9    10    11

     WPB      0     0   947  1225   519   979   440   666   475   647   630     0

     CGD1    00    00  5820  5600  5030  5320  5270  5350  6650  6600  6630    00
     CGN1    00    00   110   110   110   110   110   110   110   110   110    00
 P   CGD2    00    00  [illegible]                                             00
 A   CGN2    00    00   565  5120   544   693   560  5440   701   657   693    00
 R   TVGD  1010  1010  1010  1010  1010  1010  1010  1010  1010  1010  1010  1010
 A   TVGR    02    02    02    02    02    02    02    02    02    02    02    02
 M   TVGL     2     2     2     2     2     2     2     2     2     2     2     2
     GAIN    00    00    91    66    78   100    25    65    53    75    72    00
 T   RTU0    00    00     0     0     0     0     0     0     0     0     0    00
 Y   RTWW    00    00    00  1360  1360   136   136    00   140   175  1410     0
 P   RTTD     0     0   363    65    97   363   363   363   363   495   363     0
 E   CL      00    00   150   215  2550    00  1570   255   255    31   175    00
     DUPL    00    00    45    45    45    45    45    45    45    45    45    00
     DUPG    00    00    65    65    65   126    65    65    65   255    65    00
     DUPT  1730  1730  1730  1730  1730  1730  1730  1730  1730  1730  1730  1730
```

FIGURE 9. TABULAR DISPLAY OF SIGNAL-PROCESSOR PARAMETERS. Numeric Input Will Replace Or Increment Parameter Value For A Particular Transducer Number Selected By Positioning The Cursor As Shown, Or For All Transducers If Cursor Is Positioned Before Beginning Of A Row.

of signal-processing and display functions that the system is capable of can be accomplished from the tape-recorded signal, even after the tire is no longer available for tests.

5. PULSE ECHO SIGNALS FROM TIRES

5.1 "A-SCAN" ECHO RETURNS

Before describing the various signal-processing and display functions of the system in more detail, some of the characteristics of pulse-echo returns from tires are noted which have motivated the design of this system.

Figure 10 shows echo signals correlated with the internal structure in the tread region of a belted tire where there were four body plies and two belt plies. The upper echo signal was obtained with a transducer having a nominal resonant frequency of 1.0 Megahertz, while the lower trace was obtained with a 5.0 Megahertz transducer. The upper trace shows a sharp, three half-cycle return from the outer surface of the tire, which is characteristic of the echo signals as seen from simple plane interfaces with highly damped transducers, which must be used so that the emitted pulse is short enough to give useful resolution of the layered structure.

The return from the outer surface of the tire for the 5.0 Megahertz transducer appears more complex, merely because it is a summation of echoes from various surface elements of the tire at slightly different distances from the transducer. Reflections are seen from the deepest grooves in the tread pattern (e.g., at 5.0 centimeters on the 1-Megahertz trace, and at 4.2 centimeters on the 5.0-Megahertz trace) because the ultrasonic beam cross section (about 1 inch in diameter) is occupied partly by ribs and partly by grooves. Shortly thereafter, a larger oscillatory signal is returned from the ply layers; and finally, a pulse resembling the initial pulse in shape but inverted, and much broadened, is returned from the interface between rubber and air at the inner surfaces of the tire. The amplitude of the return from the plies decreases very rapidly with depth, more rapidly for the higher-frequency transducer, and returns from greater depths in the tire structure exhibit a low-frequency character. Since the incident pulse is short in time, it has a very broad frequency spectrum, and the returns from

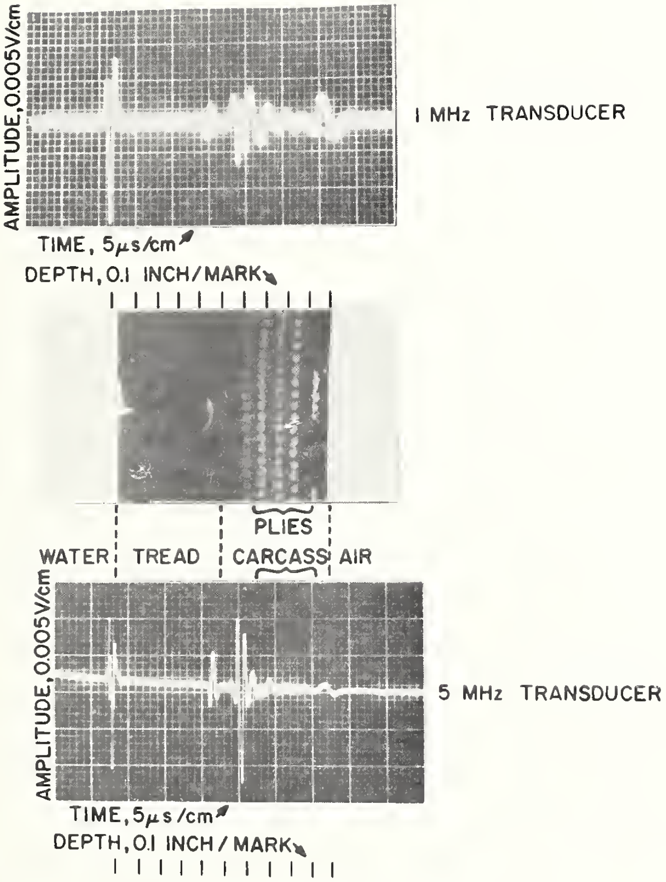

FIGURE 10. REFLECTION SIGNAL MATCHED TO TREAD STRUCTURE OF BELTED-TIRE SECTION

deep within the tire structure constitute primarily the low-frequency components of the signal which are less strongly absorbed and scattered. Because of these effects, it is not practical to use frequencies high enough to permit pulses short enough to cleanly resolve the successive layers in the ply structure. Even at the 5-Megahertz frequency, the oscillatory return from the ply structure still exhibits interference effects between the returns from the several layers.

The machine is fitted with 2.25-Megahertz transducers as a reasonable choice for the trade-off of resolution and penetration. Nevertheless, there is sufficient depth resolution to indicate the depth of the defect or anomaly relative to the various structural elements. There is certainly sufficient resolution to tell the difference between a bubble or air film on the surface of the tire and a separation or other defect within the body of the tire. The pulse-echo technique is thus inherently foolproof with respect to false-alarm indications because of inadequate wetting or entrained air bubbles which may have caused difficulties with previous immersion ultrasonic systems which used through-transmission techniques.

5.2 DIFFICULTIES OF INTERPRETATION OF DATA

Figure 10 simultaneously proves the promise of, and exhibits the fourth fundamental difficulty of, inspection of tires with ultrasonics. Ultrasound penetrates the tire structure, as is evidenced from the substantial return from the inner surface of the tire, even at 5-Megahertz, and echo signals are certainly returned from the layered structure of reinforced materials. However, the echo signal is complex. Furthermore, it is not only unique to the particular tire construction (number of plies, materials used, the thickness of tread, etc.), but the echo signal is different at every spot around the cross section of a given tire.

The situation is entirely different from that usually prevailing in metals testing, where the body of the material is homogeneous, and the presumption is that any echo from an internal volume elements represents a defect. In such a situation, a very simple form of automated processing is highly effective; a time window or range gate is established which excludes echoes from the front and back surfaces of the tested object, and echoes within this gate exceeding some established threshold correspond to defects.

In tires, the situation is not so simple. The internal volume of the tire body returns echo signals from the normally present cord structure. Echo signals from such gross defects as separations exceed the background of reflections from normal tire structure, and therefore, are detectable with gate-and-threshold techniques.

However at the time that this machine was conceived, there was increasing evidence that separations were neither a necessary nor a sufficient cause for tire failure. Thus, it appeared that more subtle anomalies needed to be investigated -- anomalies which would not necessarily give echo signals rising above the background of normally present reflections from ply structures, but which might be evidenced by perturbations of the amplitude, or perhaps, the phase of the normally-present signals.

5.3 DATA INTERPRETATION: B-SCAN

The B-scan display technique provides a very sensituve means for detecting any such perturbations of the normally present echo patterns. Figure 11 illustrates the technique with scan data taken on a programmed-defect tire having separations approximately 1/2, 1, and 2 inches in diameter, deliberately introduced between the belt and the body plies. The reflection-amplitude signal is used to intensity-modulate the beam of an oscilloscope, which is then displaced vertically in synchronism with mechanical scanning produced by rotating the tire relative to the fixed transducer. The image display shown was produced in four sections by recording the face of the oscilloscope on Polaroid film during successive 90 degree intervals of rotation.

The ultrasound is reflected from the tire, starting, of course, with the outer surface, and the farther into the tire structure the reflecting interface, the later the time at which the echoes return. Thus, the horizontal axis (corresponding to the time axis of the

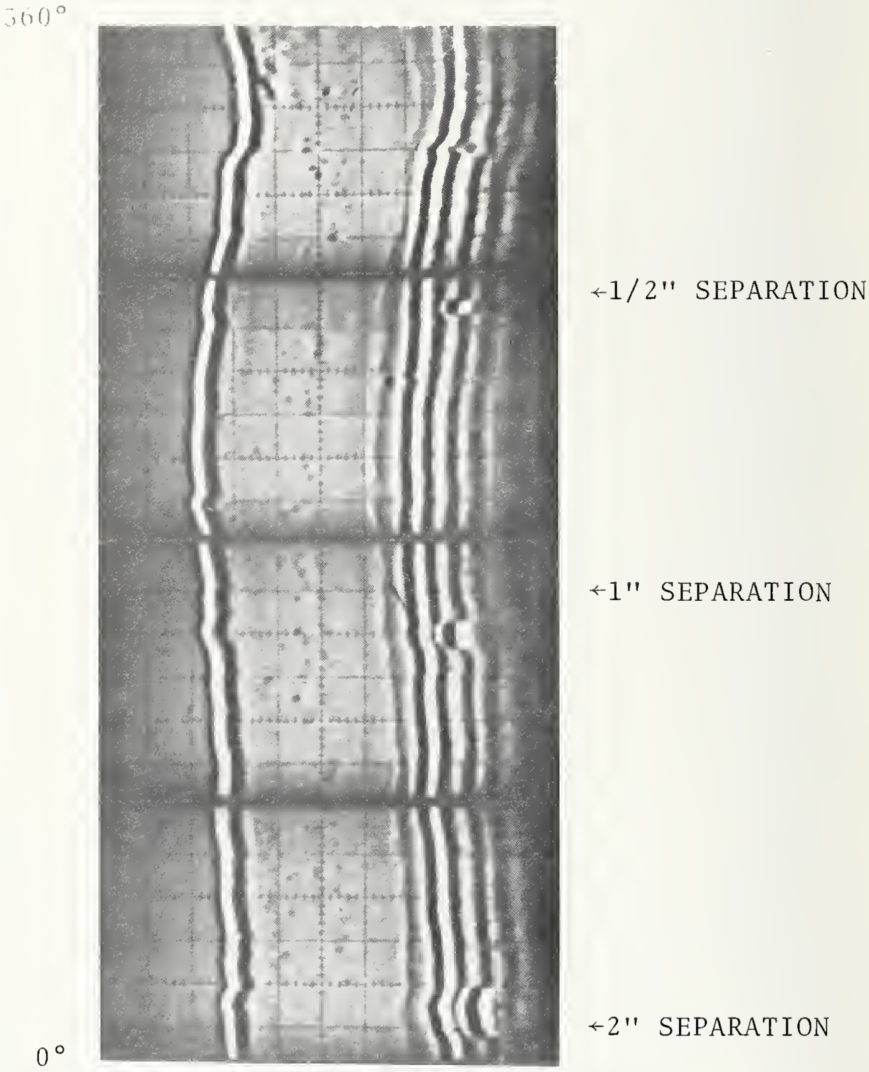

FIGURE 11. SINGLE-CHANNEL B-SCAN DISPLAY

oscilloscope) measures depth into the tire structure. The bright line at the left side of the display is the reflection from the outer surface of the tire, while the bright ridges on the right side are the reflections from the belt and ply layers. The less-intense line just to the left of the belt reflection comes from the deepest grooves in the tread pattern. Thus, the depth of the tread is measured by the horizontal distance to this trace from the outer surface trace, and the non-uniformity of the under-tread rubber is shown in the variable spacing of this line from the belt reflection. Large bright spots indicate strong echoes from the separations, clearly at a depth corresponding to the interface between belt and body plies.

The fact that the lines generated by reflections from the tire surface and ply structure are irregular; that is, that they are wavy rather than straight, indicates a lack of uniformity in the roundness of the tire, since the position of a trace, of course, is a measure of the travel time (and hence, distance) from the transducer to the reflecting structural element and back. Dimensional non-uniformity measurements can be related to force-variation measurements.

Pulse-echo ultrasonics provides a unique capability to make precise measurements of the dimensions and shape of the structural membrane of cord materials in an inflated tire. The positon of a particular structural element can be measured directly from the ultrasonic echo time, rather than inferred by measuring mechanically to the outer surface and allowing for an assumed constant thickness of rubber outside of the element. Since the velocity of sound in tire rubber is only about 10 percent higher than for water, the effect of variations in thickness of the outer rubber will be reduced by 90 percent as compared to a direct mechanical measurement.

We have seen that the B-scan display provides a powerful technique for revealing even very subtle variations in the echo returns from the tire structure. However, photographic recording would be prohibitively expensive for high-volume use, and the time delay involved in processing would be incompatible with real-time evaluation.

Both the materials expense and the processing delay are avoided by recording the display on an image-memory scan-converter tube. This device operates in some ways as a television-camera tube. It contains a semiconductor storage electrode on which an image can be written in the form of a charge pattern of varying density by scanning it with an intensity-modulated electron beam. Then, the resulting charge image can be read out by scanning the storage surface with the same electron beam to give a video signal which will display the image on a television monitor.

Our system provides a number of signal-processing and display formats, but the fundamental one is the multi-channel B-scan display illustrated in figure 12. Each of the vertical strips is a B-scan display for rotation of the tire from 0 to 360 degrees for one of the transducers disposed around the cross section of the tire. As in figure 11, the depth, or thickness dimension, of the tire structure is measured from left-to-right within each B-scan strip.

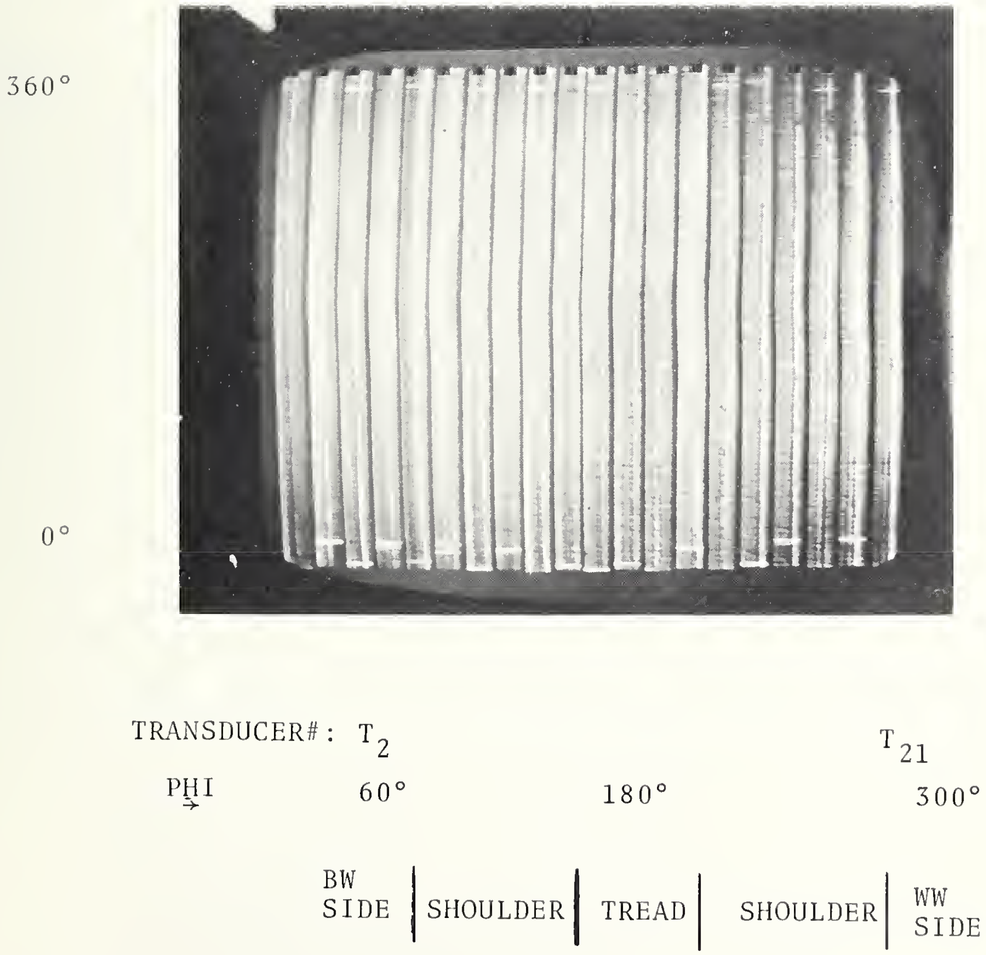

FIGURE 12. MULTI-CHANNEL B-SCAN DISPLAY (-B Signal, B-Planar Display Mode)

6. SIGNAL PROCESSING AND DISPLAY GENERATION

6.1 GENERAL PRINCIPLES

The functioning of the signal-processing and display electronics to produce displays will be explained with reference to the functional block diagram shown in figure 13. As the master clock produces timing pulses, the T-counter generates sequential transducer addresses to control the pulser/receiver multiplexer. A different transducer is pulsed every 400 microseconds, and the sequential echo signals are passed to the input of the signal-processing electronics, and also to the video tape recorder.

The block diagram is shown with the first selection switch in the SCAN position, in which case a display is generated from the signals coming directly from the tire. In the PB or playback position, previously recorded echo signals would be processed just as though they were coming live from a tire scan. The dotted lines indicate control of this switching by the lighted push-buttons labeled SCAN and PB, which can be seen in the upper righthand corner of the mode-control panel shown in figure 14.

Assuming the "B" option is selected by the next pair of interlocked buttons, the input to the signal processor will be affected by the scan-programmed gain values for each transducer, but not by the time-varied gain stage. If the "B" output of the signal-processor multiplexer is selected by the next group of mutually exclusive pushbuttons, and BPL-display-mode option is selected (i.e., all switches in the positions shown in the diagram), the echo signal is passed directly through to the Z-input to intensity-modulate the electron beam of the scan-converter tube.

The write beam is deflected to an appropriate X-position corresponding to the transducer number, and a Y-position corresponding to the rotational position of the tire, by digital/analog conversion of the transducer count value and the θ-count value. At an appropriate time corresponding to the arrival of the echo return from the tire (normally the sum of Water Path Delay and Sweep Delay),

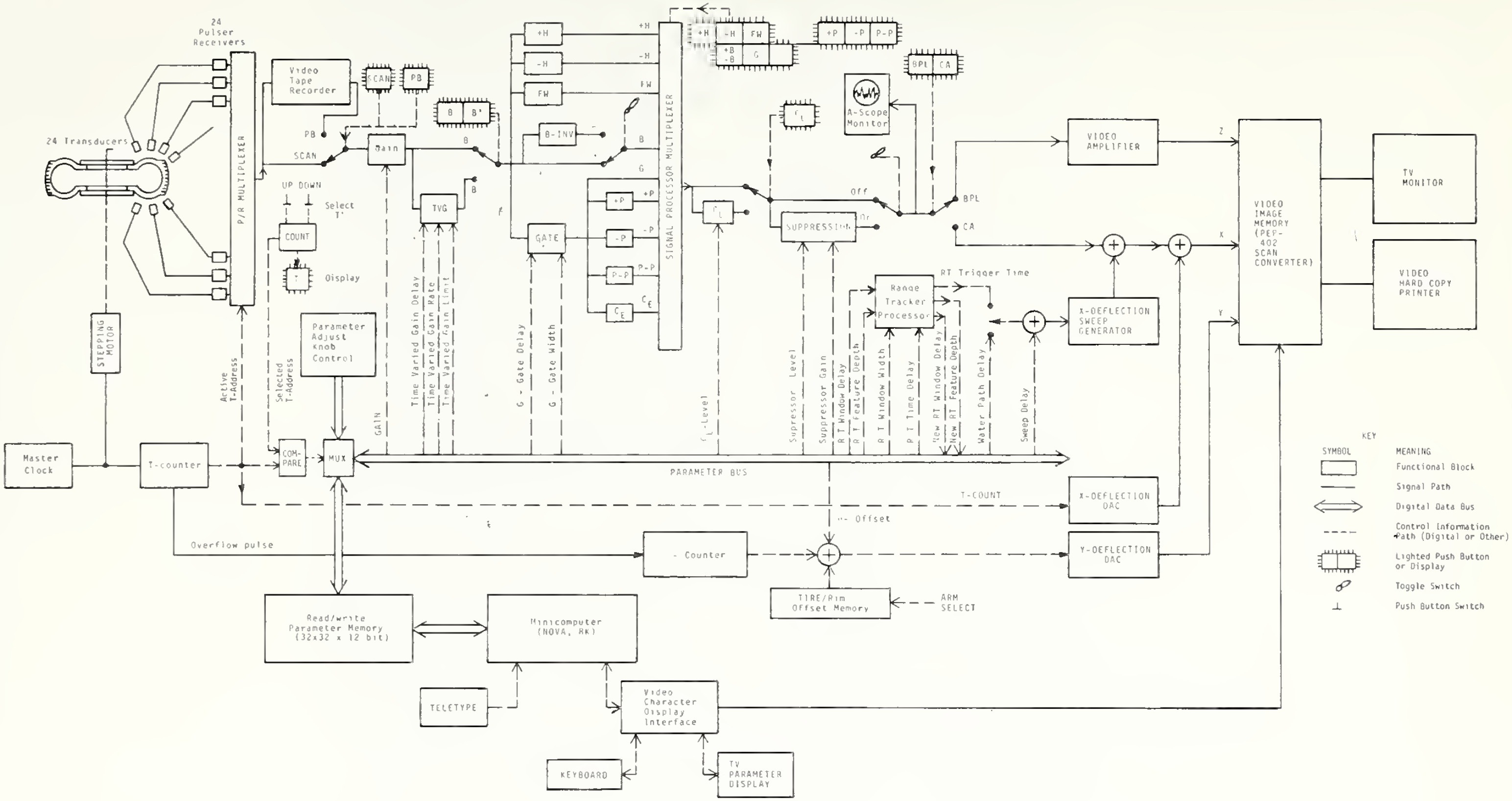

FIGURE 13. FUNCTIONAL BLOCK DIAGRAM
Indicating Signal-Processing And Display Modes

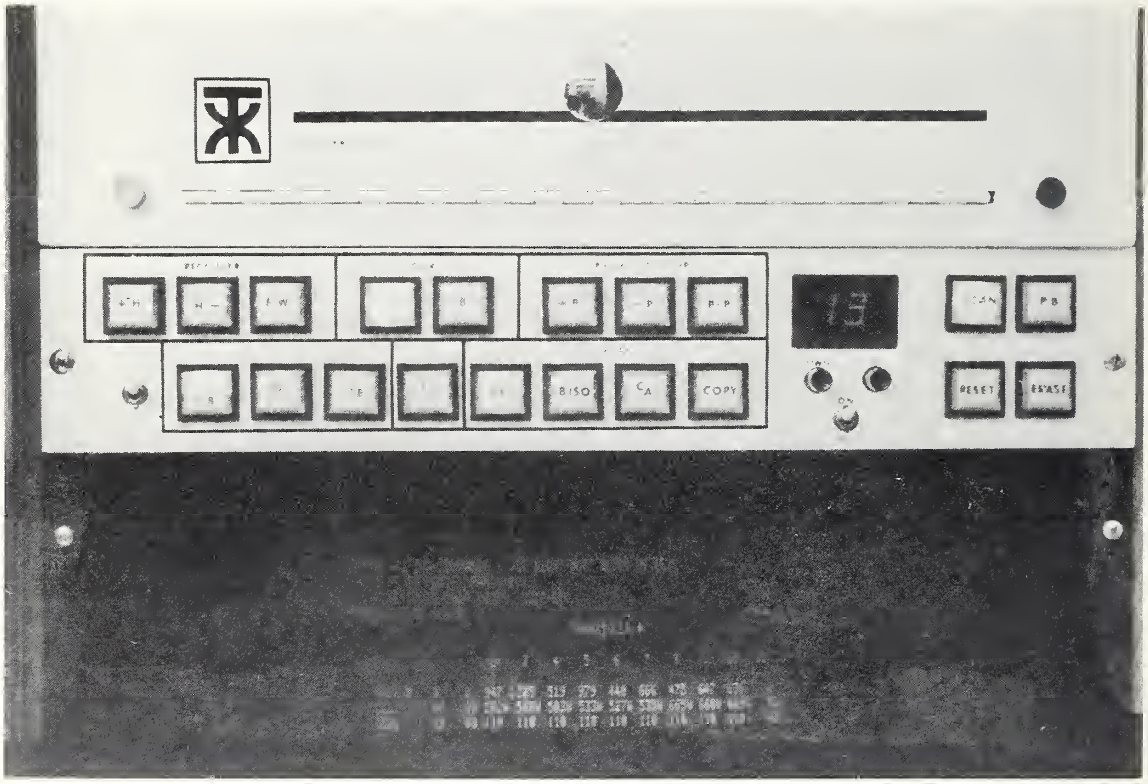

FIGURE 14. MODE-CONTROL PANEL

the write beam is unblanked for about 32 microseconds, while the X-deflection sweep generator moves the beam across the width of one of the 24 display segments.

6.2 A-SCOPE MONITOR FOR SETUP

Figure 15 shows the A-scope presentation which guides the operator in adjusting parameters and selecting processing options for the previously shown display as well as certain others. The top trace shows the output of the pulser/receiver multiplexer with the oscilloscope triggered at the time of the "main bang," or excitation pulse, for transducer number 7. At 20 microseconds per centimeter, only the echo signal from this transducer is seen. The operator will normally activate the Water Path Delay knob and adjust until the unblanking pulse covers the tire-echo signal, or as in this case, selects that part of it of most interest. The delayed sweep of the A-scope is traggered by the rising edge of the unblanking pulse, and the main sweep is intensified for the duration of the delayed sweep, which is made to coincide with the length of the unblanking pulse. The selected portion of the echo signal is shown with the expanded delayed sweep in trace 3.

In this case, the "-B" signal has been chosen to provide a maximum signal for separations, which have a negative reflection coefficient, since they represent a transition from the high-acoustic impedence of tire material to the low-acoustic impedence of air. A prominent separation reflection occurs at about 3.5 centimeters on this trace. This is the signal which was used to generate the multichannel B-scan display shown previously in figure 12, and the separation, in the shoulder of the tire, accounts for the bright white spot at approximately $\theta = 180$ degrees on the sixth B-scan strip of that figure (the zero and first transducers were not mounted and the B-scan segments are not written).

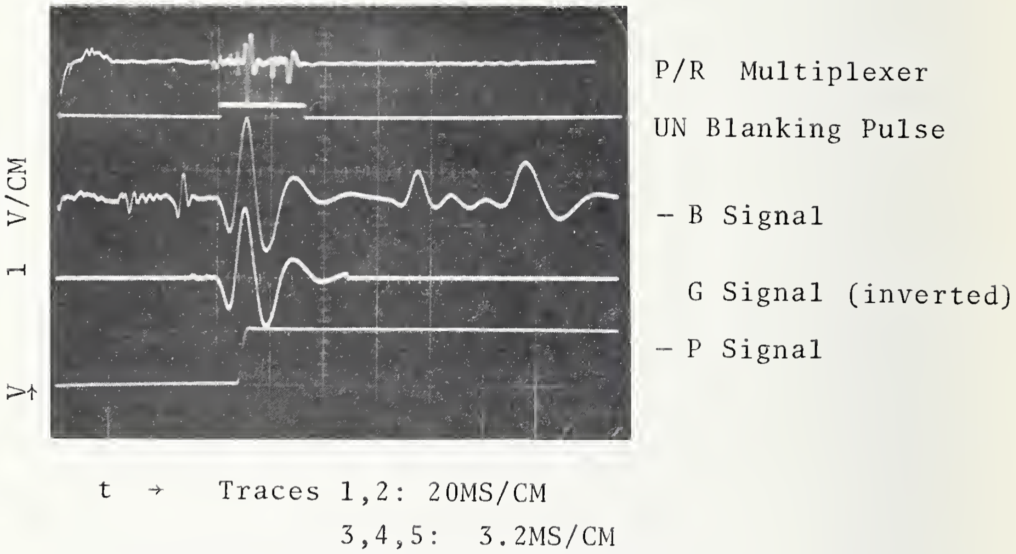

FIGURE 15. A-SCOPE PRESENTATION SHOWING PROCESSING OPTIONS

6.3 GATED AMPLITUDE GO/NO-GO EVALUATION

Tires can easily be tested on a go/no-go basis for defects such as separations, which give large signals compared to the background signals in their immediate neighborhood. The G-pushbutton is pressed, whereupon the button is lighted to indicate that the G-signal is the selected output of the signal processor multiplexer. The G-Gate Delay and G-Gate Width knobs are activated and the gate is positioned to include the desired depth region in the tire. Then, a rectification mode is selected, in this case "-P", since the negative peak is the most prominent feature of the separation. The "-P" signal rises in a positive direction proportionately to any negative peaks within the gate and remains at the largest amplitude reached until it is reset for the next transducer signal.

In the B-planar display mode, this signal intensity-modulates the display as before but the brightness level is constant once the largest peak is reached, and the result is as shown in figure 16. The format is the same as for the B-scan display; but each trace starts at the background level, and then, goes to a constant brightness level measuring the peak amplitude. The depth into the tire at which the peak amplitude is reached depends on the gate setting. Traces with early gate settings appear bright over much of their width, while those with late gate settings are bright only at the right-hand edge corresponding to the lower depths in the tire.

If the C_A pushbutton is pressed, the C-analog display mode is selected, and the peak amplitude is used to deflection-modulate a trace for each transducer as shown in figure 17. The shoulder separation appears prominently on the sixth trace at a position corresponding to approximately θ = 135 degrees on the scale. (The shift in θ-position resulted from operator error; normally, registration is maintained for successive scans on the same tire.)

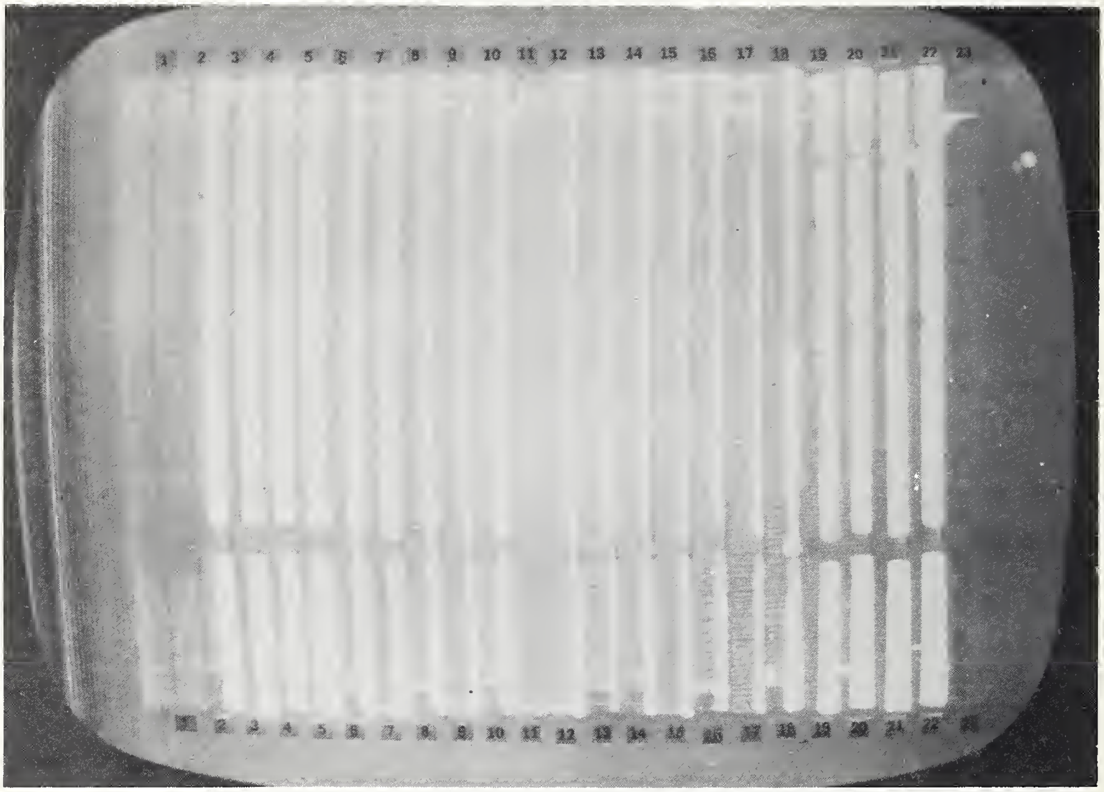

FIGURE 16. C-SCAN DISPLAY IN B-PLANAR DISPLAY MODE
Gated And Peak-Rectified Signal Intensity Modulates Display.

In the parlance of ultrasonic testing, both of the last illustrated displays are "C-scans". A single quantity is derived for each pulse measuring some attribute of the signal within a time window or gate, and this result is plotted in a two-dimensional display, both axes of which correspond to mechanical coordinates. In our case, the two axes of the display correspond to surface coordinates on the tire. The vertical coordinate is the θ-direction generated by rotation of the tire, while the horizontal axis is the ϕ-direction corresponding to transducer position around the cross section.

The final step in go/no-go evaluation of the signals is provided by the C_L-module, which compares the selected output of the signal-processor multiplexer with scan-programmed threshold settings, which, of course, can be different for each transducer. If the measured attribute of the signal exceeds the threshold, a saturation-level output is generated which will print a white spot using the B-planar display, with the result shown in figure 18. The shoulder separation on channel 17 (printed sixth from the left), which we have been examining, is clearly evident. In addition, a smaller separation is evident at approximately $\theta = 45$ degrees. This separation is discernable on the ordinary B-scan. Incidently, the solid white bars which go all the way across each B-scan strip on all of the B-planar displays are electronic artifacts, which have since been eliminated. The bright white spot at about 1/3-depth into the tire on the display for transducer 16 at about $\theta = 90$ degrees is an artifact of the scan-converter tube.

6.4 VERSATILITY OF PROCESSING AND DISPLAY COMBINATIONS

As has been illustrated by a number of examples, any of the processing options indicated by possible switch selections and multiplexer-output choices indicated on the functional block diagrams can be used in combination with either of the display formats. The A-scope presentations for some more of the signal-processing options are shown in figures 19 and 20. The +H (positive half-wave rectified), the -H, and the FW (full-wave rectified) outputs are intended primarily for enhanced B-scan displays.

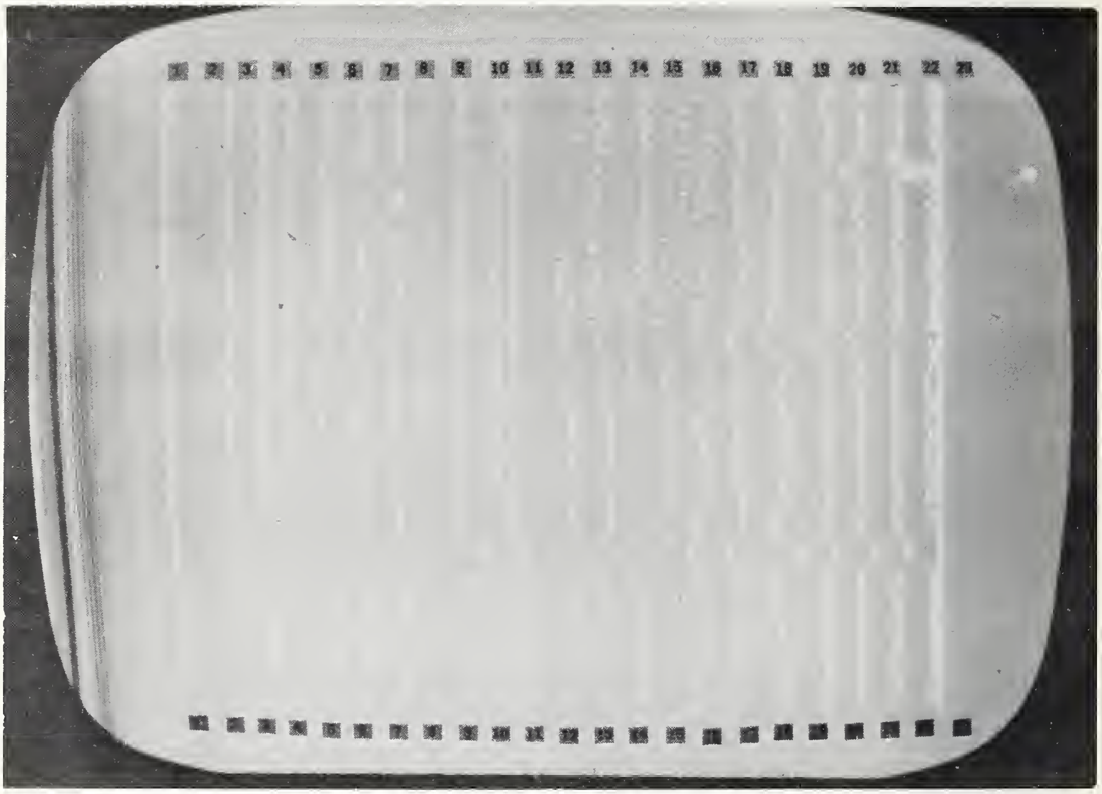

FIGURE 17. C-ANALOG DISPLAY
Amplitudes Of Gated Signals
Deflection Modulate Traces.

FIGURE 18. C-LOGIC/B-PLANAR DISPLAY
Logic Signal Triggered Whenever Selected
Signal Exceeds Threshold Intensity
Modulates Display.

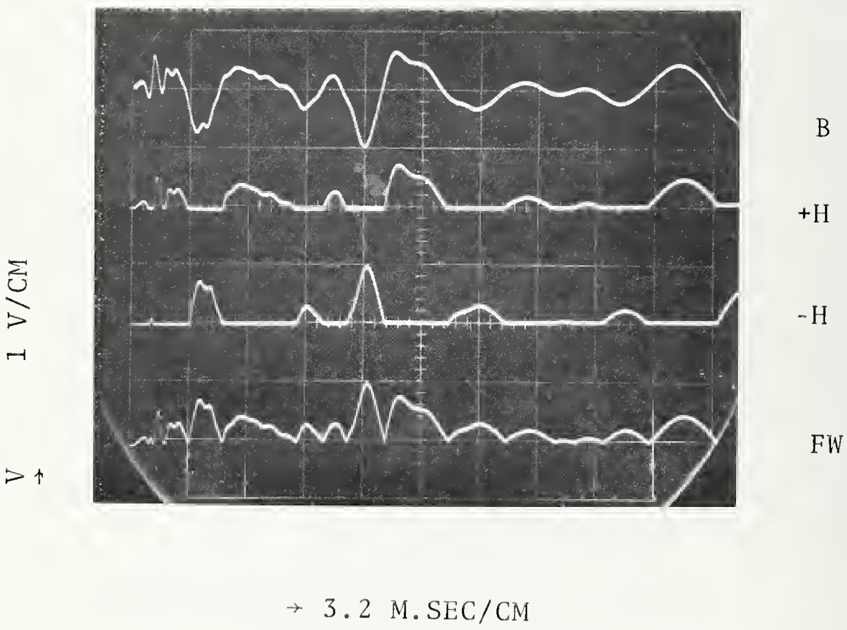

FIGURE 19. PROCESSOR OUTPUTS FOR B-SCAN DISPLAYS

6.5 TIME VARIED GAIN CAPABILITY

The B' signal is the original echo signal modified by programming the amplifier gain to increase exponentially, beginning at a certain onset time. The onset time (i.e., delay), the rate of increase, and a limiting value for gain increase are all scan-programmable. As shown in figure 20, this capability can be used to compensate for the attenuation which causes reflection amplitudes from the deeper ply layers to be smaller than for the outer layers. Besides enhancing a B-scan display, this provision is helpful in setting an automated-detection threshold to be equally effective for defects at all depths. For this purpose, the inner-surface reflection, which is much larger than the leveled ply signals, would be excluded by the gate.

6.6 AUTOMATED TRACKING OF STRUCTURAL FEATURE DEPTHS

For automated detection of defects, one would generally want a measuring gate to cover that part of the reflection signal attributable to some particular structural element in the tire; for example, the outermost belt, the region between belts and body plies, the inner surface reflection, etc. While it is easy to set the gate delay and gate width so that any desired condition applies at a given spot on the tire, the amount of runout in tires is such that a setting made for one spot cannot be depended upon for the whole rotation of the tire. The usual answer to this problem in ultrasonic-testing is what is called "first interface gating"; i.e., a timing signal is derived from the reflection from the first surface encountered in the tested object, and gate position is measured with respect to that signal.

In the case of tires, this procedure appears undependable because in some cases there are serious variations in the thickness of some of the layers. Therefore, a range-tracking capability was specified in the design of this system. This permits a timing signal to be referenced to any prominent feature in the tire-reflection signal, even to features which occur later than the timing-signal itself. Actually, the time is referenced to the occurrence of the feature on the preceding pulse on the same

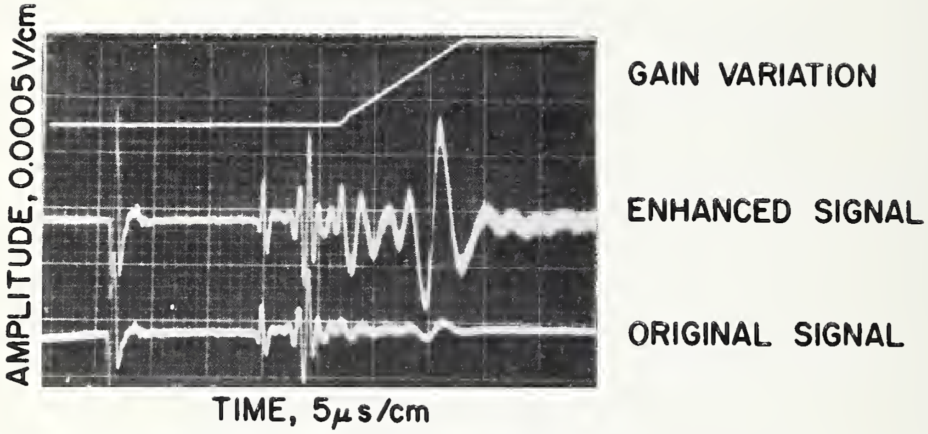

FIGURE 20. TREAD REFLECTION ENHANCED WITH TIME VARIED GAIN (T54, 5 MHz TRANSDUCER)

transducer. This capability is implemented through a special digital processor which uses the resources of the digital-control system.

All of the signal-processing time measurements are accomplished by counting cycles of a 20-Megahertz pulsed oscillator, which is started afresh with each "main bang." A time to be measured (for example, the Water Path Delay) is loaded as an initial setting for a counter which counts down at the 20-Megahertz rate. A timing pulse is generated when the counter reaches 0 and underflow occurs. The range-tracker processor establishes a trigger signal gate or window, adjustable in delay time (Range Tracker Window Delay) and width (Range Tracker Window Width).

If the signal passes a threshold setting within this gate, a counter is stopped to measure the time of occurrence of "Feature Depth." The Feature Depth so determined is compared with the Feature Depth found on the preceding pulse, which was supplied from the parameter memory. If the Feature Depth has changed, appropriate adjustments are made to the window position and to the range-tracker trigger time by digital addition or subtraction, and the new values are stored back in the parameter memory until the same transducer is to be served again. Since the parameter memory at all times has stored the current values of the Feature Depth for each of the transducers, and since data paths from the parameter memory to the minicomputer are already established, we are very close here to a capability for digital acquisition of 24,000-dimensional measurements on the tire to any acoustically observable features within the tire structure.

All of these considerations are concerned with efforts to apply conventional gate-and-threshold detection criteria to automated detection of anomalies in tires. Indeed, automated detection appears to be entirely practical for gross anomalies, provided that one optimizes the adjustments of time varied gain, gate positions, threshold heights, etc., to suit the particular type of tire being inspected. However, to detect possible anomalies which would perturb the normally-present reflections, but which would not necessarily generate signals that rise above their average level, prinicpal reliance must be placed at this time on operator evaluation of the B-scan display.

6.7 ZOOM CAPABILITY

Operator evaluation of the displays is immensely aided by the zoom capability of the scan-converter tube memory. A small region or window on the surface of the image-storage electrode is scanned and the resulting signal is displayed full-size on the television monitor. With such electronic magnification, the resolution of the television monitor contributes no limitation, and the full resolution of the scan converter memory is obtained. Magnified displays of two regions selected from the previously presented scan are shown in figures 21 and 22.

Figure 21 shows the region in the neighborhood of the shoulder separation. It is evident that the separation extends to the next adjacent trace as well. Figure 22 shows the display in the vicinity of the bright spot in the channel 16 segment attributed to an artifact on the scan-converter tube surface.

A perfect tire would be at least rotationally symmetrical, and the display would show a series of vertical lines which would be completely straight and uniform. These displays show many instances of irregularity which must be considered normal, and we are still learning to relate anomalies in the display to irregularities in the tire. Furthermore, a great deal of work still remains to be done to relate observable anomalies to tire performance.

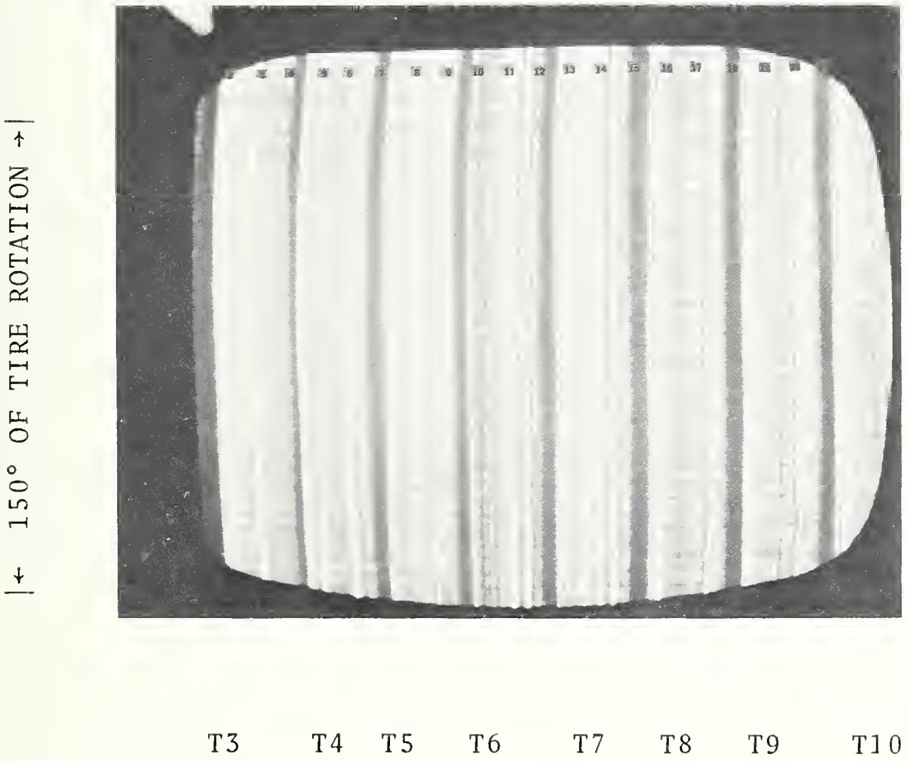

FIGURE 21. B-SCAN ZOOM DISPLAY - NO. 1. Region Of Shoulder Separation Visible In Figure 12.

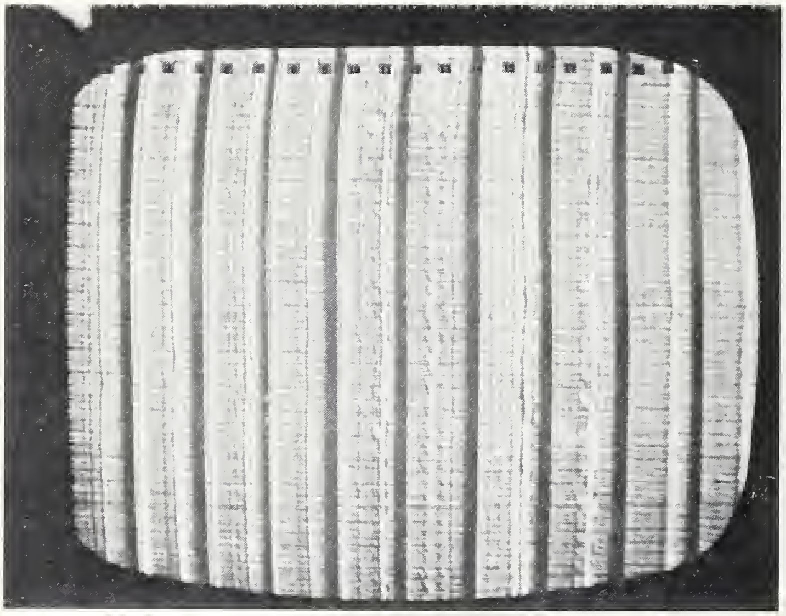

FIGURE 22. B-SCAN ZOOM DISPLAY - NO. 2. Region In Lower Right Of Figure 12. T_{13} Shows An Indication Of A Small Separation Between Tread And Body Plies. T_{15} And T_{16} Show Perturbations Of The Inner Surface Traces Suggesting Possible Separations, But Probably Caused By Splices. The Bright Spot On T_{16} About 1/4 Way From Bottom Is A Display Artifact.

7. COMPUTER-AIDED PARAMETER MANAGEMENT

We have seen that a large number of parameters must be set to define any sort of go/no-go test criteria or even to produce an optimized display for operator interpretation. Furthermore, all of these parameters have to be adjusted to suit the particular type of tire being inspected. The minicomputer installed in the system helps the operator to manage all of the parameter data. The actual scan-programmed digital control is all implemented in special hardware and the system will operate without the computer. However, the computer accomplishes a very major reduction in the operator's burden. The software is very elegantly designed to communicate with the operator through an alphanumeric video display, and to guide the operator in the operation of the system.

The menu of options shown in Figure 23 is displayed and the operator makes his selection by keying in the appropriate option number and striking the "action" key on the keyboard. For example, option 1 transfers a parameter set from the hardware parameter memory to the computer memory. A basic purpose served here is that the computer memory is magnetic core, which is nonvolatile, (that is, the stored data are retained even when the power is switched off), whereas the hardware memory is all-electronic, and hence, is volatile.

Option 6, "Modify Data Set From Keyboard", gives the tabular display we showed earlier in figure 9. When the cursor on the display is placed to the left side of a particular table entry, the action key opens up space for a new line in the table, and the operator can enter a new value or a plus or minus change. If the cursor is positioned all the way to the left side at the label column, a keyboard entry will affect all 24 transducer channels in the same way, which provides a convenient way to make initial settings or global changes. A record of the settings used for any given test can easily be produced by copying the tabular display to the scan-converter memory, and then to the hardcopy video printer.

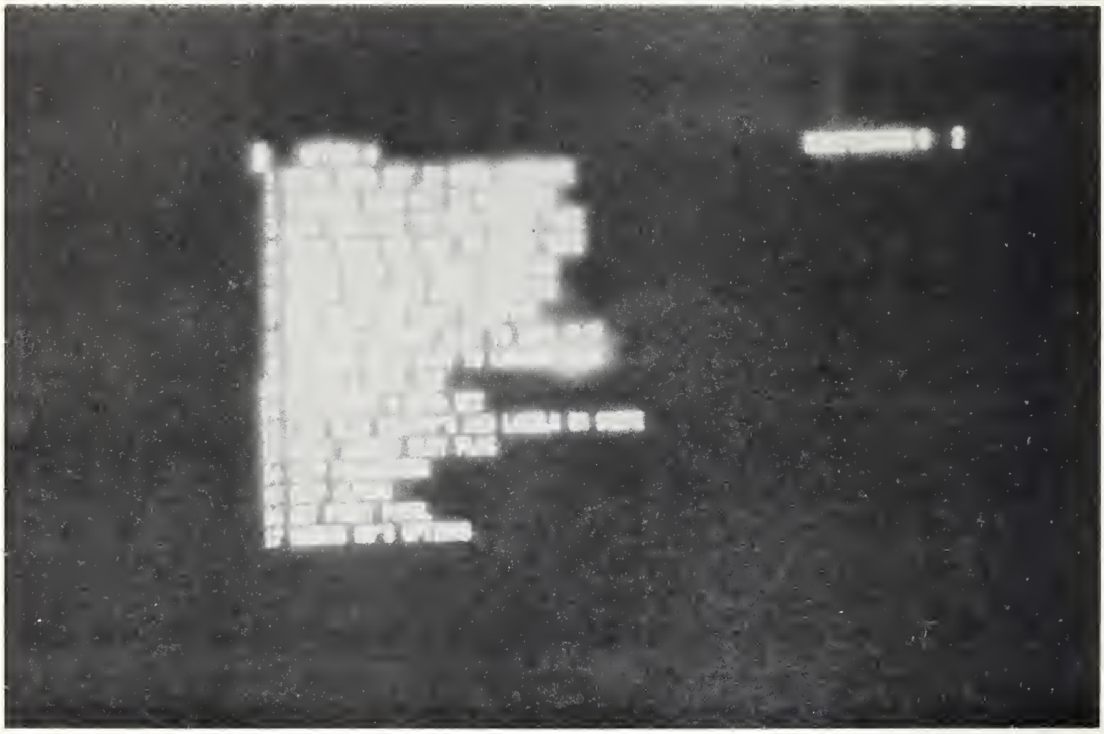

FIGURE 23. SELECTION "MENU" FOR PROGRAMS TO MANIPULATE PARAMETER SET DATA

Options 3 and 4 provide for transferring parameter sets to and from paper tape. A modest addition of cassette tape or diskette peripherals would permit file-oriented storage of parameter sets, so that an operator would only have to key in an appropriate code to retrieve a data set previously arrived at for a particular type of tire. Besides loading the parameter-set values, the computer can set standard or initial values for the α-angle alinement adjustments by outputting appropriate numbers of stepping motor counts for each channel. Coarse gain settings made on the individual pulser/receiver cannot be set by the computer, but the manual settings made can be read by the computer and checked against the intended settings.

8. CONCLUSIONS

The general philosophy of the system design has been to recognize that while pulse-echo ultrasound provides a powerful capability for inspection of tires, it is inherently complicated by the complexity of internal structure and the unusual shape of tires. This basically geometrical complexity requires a rather complex setup to suit the individual tire before the full capabilities of the technique can be realized.

In the system designed, the major burden of this complexity has been engineered into the system, and the operator has been relieved of as much of the routine bookkeeping as possible. Further, the use of digital-control techniques permits the setup adjustments to be stored and re-used, so that the labor of arriving at them for various sizes and designs of tires need not be repeated. While this line of development has not been carried to the ultimate lengths that one might desire for production use with a highly mixed population of tires, it has been carried far enough to be highly efficient for reasonably long runs of identical tires.

For such runs, inspection times for the system as now implemented would be about 2 minutes per tire if the signals are merely acquired to video tape or processed to a single display for automated defect detection. Additional time would be added for real-time interpretation of the data displays, depending on the questions of interest and the degree of thoroughness desired. It is worth noting, however, that these inspection times are primarily limited by mechanical considerations. The ultrasonic limitation is to approximately 2 seconds for the data-acquisition scan. With totally automated interpretation, which is possible now if the rejection criteria can be made specific, a throughput of six tires per minute does not seem unreasonable for a highly automated ultrasonic tire-inspection system.

The projections as to the feasibility and practicality of pulse echo inspection of tires made in Reference 1 (Ryan, R.P., "Feasibility of High-Resolution Pulse-Echo Techniques for Automobile Tire Inspection," PB-231-201, DOT-TSC-NHTSA-72-11, June 1973) on the basis of small scale tests, have been amply confirmed by the building of the full scale machine. Ample penetration with sufficient thickness resolution to relate the depths of indications to the laminar structure is readily obtained for all presently used tire constructions. The video display techniques have proved to be a practical and effective means for dealing with the normally-present signals from the laminar structure of tires, and provide a powerful capability for revealing non-uniformities, i.e., localized anomalies in materials, structure, or geometry. This capability for detecting localized anomalies has been found to be of immediate use to NHTSA for detection of internal degradation induced by the potentially destructive tests prescribed by the presently established safety standards.

However, the capabilities of pulse echo ultrasonic measurements for quantitative characterization of the composite materials in tires have not yet been fully exploited. The present system has circuitry for deriving an analog voltage which measures certain attributes of the echo signals, specifically, the amplitude (positive or negative peak, or peak-to-peak) of the echo signal within a particular depth range. The video displays, particularly the C-A display shown in Figure 17, show the variation in such an attribute as the tire is scanned under rotation. Again, the analog display techniques are extremely effective for revealing localized regions where the properties of the tire differ from the rest of the tire, but are ineffective for finding tires which, as a whole, differ significantly from the norm for their design.

Yet, it is just such differences that would be most meaningful in the testing of tires for compliance with safety standards. The entire NHTSA safety standard enforcement program is oriented toward the identification of bad production lots which would justify recall action, or bad tire designs which should be withdrawn from the market. Localized anomalies are most likely to result from random errors in the hand building process, accidental contamination at specific spots, etc., events which at best will have only weak statistical implications with regard to the quality of a production batch. (See reference 2.)* On the other hand, mean measures of tire characteristics would be inherently responsive to possible batch-related production errors, such as improper formulation of a rubber mix, variations in raw materials characteristics, process variations in the calendering of sheet and cord materials, improper curing (which might possibly occur because of variation of the rubber batch, or an error in the cure specification), or errors in programming of the materials flow in the production process such that the right materials are built into the wrong tires, or into the wrong places in the right tires.

A very modest addition of digital data acquisition capabilities to the present system would establish a very powerful capability for deriving various mean measures of tire characteristics, and would permit evaluation of the effectiveness of such measures for identification of bad batches of tires. The system already contains most of the required resources. There are unused words in the control memory, which could be used for temporary storage of A/D converted values corresponding to analog measures of the depth-gated amplitudes of the echo signals. Hardware and software interlocks are already worked out to permit transfer of data between the control memory and the NOVA minicomputer during the operation of the system, and the NOVA is totally uncommitted during the scan, once the parameters are set up. Thus, all that is required is the addition of an A/D conversion module and control and timing logic to store values in the control memory, plus addition of a suitable

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*Reference 2 (Bobo, S.N., "Preliminary Study of the Relationship Between Failure of Retreads during FMVSS 109 Tests and Flaws Detected By Non-Destructive Testing," DOT-TSC-NHTSA-73-1, August 1973) presents data showing statistically greater incidence of failures in populations of tires having statistically greater incidence of separations, but with poor correlation on a tire-for-tire basis.

mass storage peripheral (tape or disk) to which the NOVA could transfer the data. Initially, data processing could most economically be done on a large computer system (such as the in-house PDP-10) having generous software and hardware resources, to minimize the cost of experimental programming at the minicomputer level. There is little doubt that mean measures found useful could ultimately be implimented on the dedicated minicomputer, so that the system would remain self-contained.

9. RECOMMENDATIONS

Based on the above conclusions, the following recommendations are made with respect to the work required to realize the full benefits of ultrasonic inspection of tires:

a. The display characteristics corresponding to all the known types of localized anomalies should be documented by cataloging representative displays in relation to the physical evidence revealed by destructive tests, e.g., photographs of dissected tires, results of peel tests, etc. Personnel working with the technique have learned to relate the display indications to such anomalies, but systematic documentation is needed to communicate this knowledge to others.

b. Add data acquisition capabilities to the present system as discussed in the Conclusions section above, and investigate various mean measures of tire characteristics by trial analysis of data from small samples of tires having known batch anomalies, or groups having known differences.

c. Using large samples of tires, evaluate the extent to which road service and road-wheel failures can be correlated with specific anomalies on a tire-for-tire basis, and with both the incidence rates for localized anomalies and with various mean measures of tire characteristics on a population-by-polulation basis.

d. Depending on the results of the work described above, the pulse-echo ultransonic inspection technique will then be recommendable, either for NHTSA use in connection with compliance testing, or for industry use for production quality control, or both.

If correllation with tire failures should be demonstrated principally with respect to localized anamalies on a one-to-one basis, and the incidence of such anomalies is not significantly batch related, the technique will be of principal benefit for production quality control, where it could serve to screen the bad individual tires from otherwise good production batches of successful tire designs.

If satisfactory correlation with tire failures should be demonstrated for any batch-related measures of tire characteristics, including possibly the incidence rates for particular localized anomalies, a basis will have been established to recommend the use of the technique in connection with compliance testing. The first step could be to use the technique to screen larger samples of tires to identify tire populations most likely to fail the established destructive tests, thereby greatly increasing the statistical effectiveness of compliance testing, without changes in the regulations. The experience obtained in such high-volume use could eventually establish an adequate basis for evolution of the regulations to place greater reliance upon the nondestructive tests, thereby greatly reducing the dependence on expensive destructive tests.

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