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Railroad Rail Flaw Detection System Based on Electromagnetic Acoustic Transducers

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16. Abstract

This report describes the design, construction and preliminary testing of an ultrasonic inspection vehicle intended for the detection of flaws in railroad tracks that are in commercial service. It differs from existing inspection systems in that it employs an ultrasonic transducer that does not require any kind of coupling liquid between the sensor head and the rail. Thus, the operation of the system is simplified, lubricated rails are inspected without special cleaning processes and there is a potential for higher speed scanning of the rails. In addition, the couplant-free transducers are able to utilize special ultrasonic wave types that increase the probability of detection of certain transverse defects in the head of the rail and vertical split head defects in the web. A computer has been incorporated into the data processing channel to allow recording of all the ultrasonic signals as well as for presenting the operator with deflections on a strip chart recorder that both act as alarm indications as well as provide information on the characteristics of the flaw. By permanently recording each ultrasonic response, the data can be reanalyzed at different sensitivity settings at a later time so that more detailed examinations of the track can be carried out off-line without interference with the normal use of the railroad.

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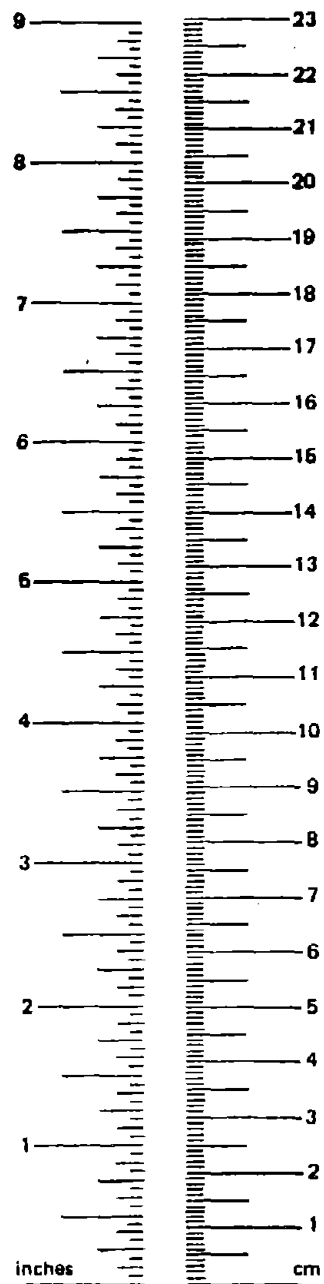
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

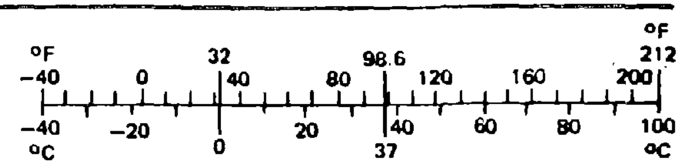
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



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	36	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



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1.0 EXECUTIVE SUMMARY

In order to improve the safety of rail transportation, installed tracks must be inspected periodically for flaws that could cause derailments. The objective of this program and its predecessor (DTFR53-80-C-00121) is to improve the reliability and efficiency of rail flaw detection by the introduction of new ultrasonic transducers that overcome some of the drawbacks of the currently used devices. These new transducers utilize electromagnetic induction across an air gap to excite and detect ultrasonic waves in the head of the rail and thus eliminate the necessity for supplying a liquid couplant to the rail. This simplifies the inspection process and the transducer support structure so that it is now possible to operate at higher inspection speeds and on rails covered with lubricant. In addition, the electromagnetic transduction mechanism makes it possible to use special types of ultrasonic waves that are more sensitive to certain flaw types than the waves generated by conventional, piezoelectric transducers.

The program described in this report applies to the results of laboratory tests to the design and construction of a self-contained inspection trailer that can be used by a normal rail inspection crew on an operating railroad to collect data for comparison with the currently used inspection techniques. Since the electromagnetic transducer is a new device that is still in the development stage, some changes in the transducer were introduced between the laboratory phase carried out by the Rockwell International Science Center and the field application study reported here. These were a reduction in the mass and dimensions of the magnet used to detect flaws in the web of the rail and a change in the transduction mechanism used to detect flaws in the head of the rail. This latter modification permitted a reduction in size and weight of the head inspection transducer and it increased the efficiency of transduction for a majority of rails. Unfortunately, tests on a large sample of track at the Transportation Test Center in Pueblo, Colorado, during the final stages of this program indicated that up to 20% of the rails may exhibit a lower than normal transduction efficiency and thus may not receive a satisfactory level of inspection at the normal settings of the instrumentation. Introduction of more powerful electronics, larger and more efficient transducers and improved signal processing should easily overcome this difficulty.

The new transducers are called Electromagnetic Acoustic Transducers or EMATs and consist of a coil of wire held close to the metal being inspected and a magnet to flood the area under the coil with a large magnetic field. By controlling the direction of the field and the detailed shape of the wires in the coil, ultrasonic shear waves can be launched into the head of a railroad rail in any direction relative to the normal to the rail head. For inspecting the head, this direction was chosen to be very close to 90 degrees and the direction of polarization of the shear wave was chosen to be parallel to the surface of the head. Such a wave is called a Shear Horizontal or SH wave in geophysics and it has special properties that make it well suited to detecting transverse defects that lie close to the top surface of a rail. In this report, we refer to this wave as the 90° wave because of its direction of propagation. The other wave discussed in this report is called the 0° wave because it propagates at 0 degrees to the head normal direction and thus reflects from the base of the rail after traversing the web. It was demonstrated by Rockwell International that if the 0° wave was polarized perpendicular to the web, the attenuation caused by a vertical split head type of defect was abnormally large and such defects could therefore be detected with higher reliability than with the longitudinal wave generated by conventional, liquid coupled piezoelectric transducers.

In order to make a self-contained, field worthy inspection vehicle for comparison with the currently used inspection systems, the 0° and a 90° EMAT units are mounted on separate carriages above one rail on one side of a rectangular frame that is supported on the rails by four flanged railroad wheels. This frame is balanced on two rubber highway wheels that can be raised or lowered so that the entire structure can be transported along a highway or along a railroad track by any kind of towing vehicle. Only two EMATs on one side of the frame were tested for this report in order to avoid the expense of modifying and upgrading four EMATs if the results indicated that such actions were necessary. As a result, the inspection data reported were all obtained by an inspection of only one rail. All the hardware needed to attach improved EMATs to the other side of the frame are already available so the expansion of the system to be capable of inspecting both rails simultaneously can be easily carried out. The electronic instrumentation needed to process the signals from the two (or four) EMAT carraiges is contained in a weatherproof cabinet mounted on the front of the frame. A system control chassis and the Compaq computer are connected to the rest of the instruments through a long umbilical cable so that these components can be mounted in the towing vehicle where an operator can use them during an inspection run. Power to the entire inspection trailer is supplied by an 8 kva motor-generator set that supplies the direct current for the magnets and the 110 volt ac for the electronics.

Extensive use of a computer is made in order to: (1) control the operation of the inspection trailer, (2) preprocess the ultrasonic data for presentation to the operator and (3) store all of the data in digital format on a hard disk memory. With all of the data stored, an operator can reexamine the data at his leisure to investigate questionable areas and to determine the consequences of setting his gates and thresholds at different levels. The preprocessing of the data for display is important because it allows the operator to set thresholds that screen him from "noise" while passing flaw-like signals. For the EMAT inspection system, noise is suppressed by programming the computer to require that the same flaw-like signal occur twice in succession before it sends signals to the strip chart recorder being monitored by the operator. Since some flaw signals may come and go faster than the pen of the recorder can respond, the computer is also programmed to examine the signals in groups of ten and to deflect the recorder pen if any signals appear to pass the flaw criteria. Thus, the recorder can have a response time ten times slower than the incoming data rate and still display useful information to the operator. In order to have the recorder convey even more information, the computer keeps the pen of the recorder at midscale under normal conditions and moves it upward in proportion to the amplitude of any "flaw" echo signals and downward in proportion to signals that measure the instantaneous efficiency of the EMAT. This latter signal display capability is unique to the EMAT system and uncovered the fact that some of the rails were receiving a less sensitive inspection.

Following construction and testing of the EMAT inspection trailer in Albuquerque, New Mexico, it was delivered to the Transportation Test Center in Pueblo, Colorado, for evaluation by the Nondestructive Testing Group at that facility. The results of their examination showed that the system correctly detected and identified rail ends, bolt holes, field welds, grounding pin holes in the web, intentional holes on the head and web designed to simulate flaws, head-web separations, bolt hole cracks and transverse defects in the head of some rails. Other, known transverse defects were difficult to detect because they were in severely worn rails where the efficiency of the transduction was found to be abnormally low. More detailed studies of the response to normal bolt holes will have to be carried out in order to decide on the minimum length of bolt hole cracks that can be detected. Careful adjustment of the operating frequency for the 90^{o} EMAT channel will have to be performed to minimize reflections from shallow cracks in the head of worn rails while still retaining good sensitivity to transverse defects in the upper part of the head. Since large variations in efficiency of transduction were observed in both the 0^{o} and 90^{o} channels, some form of automatic gain control should be added along with improvements in the transducer geometry and transmitter power.

In general, the absence of the couplant fluid allowed the system to inspect lubricated rails and made the system more convenient to operate on dry rails. However, the use of a computer to display more information on the strip chart recorder added sufficient complexity to make the system very difficult to adjust; especially when some rails exhibited poor signal-to-noise ratios. It is recommended that more efficient EMATs be installed on both sides of the trailer and more experience be gained in adjusting the parameters that influence the strip chart recorder. Also, the capabilities for off-line analysis of the data recorded in memory needs to be more fully exploited.

2.0 INTRODUCTION

The inspection of railroad rail for flaws and defects that develop during the service life of the rail has always been an important problem for the railroad industry. Most of the modern techniques of performing the inspection are based on ultrasonics because it can interrogate the entire volume of the rail in a few microseconds. Therefore, it is capable of detecting anomalies in the rail head and web from a sensor being scanned along the head by a car moving at speeds of 10 to 20 mph. Such rates of inspection are demanded in order to match the normal usage of the railroad tracks. Currently, several of the problems that limit the performance of ultrasonic inspection systems are associated with the liquid coupling medium that must fill the space between the piezoelectric transducer and the rail head. This couplant must be carried in bulky tanks on the inspection vehicle and it not only limits the top speed of inspection but it does not provide coupling on rails that have been recently lubricated or are at extremes of temperature. Furthermore, the types of sound waves and their trajectories within the rail are limited compared to all the possibilities that modern ultrasonic techniques can bring to bear on an inspection problem.

A program was initiated in 1980[1] to see if a new kind of ultrasonic transducer called the Electromagnetic Acoustic Transducer or EMAT that does not require a couplant fluid could overcome some of the problems that limit the piezoelectric device and thus make possible significant improvements in the speed and reliability of ultrasonic inspections. After some early feasibility tests indicated that the new transducer could simulate the performance characteristics of the conventional transducer, the DOT funded a major development program[2] at the Science Center of Rockwell International Corporation to test the concept on actual tracks belonging to the Santa Fe Railroad and the Transportation Test Center in Pueblo, Colorado. In the final report of this work,[3] it was recommended that a complete inspection vehicle be assembled and its performance compared with inspection systems currently being used by the railroad industry. In addition, it listed the unique features of the new transducer that were to be exploited. These were:

a. The transducer was to operate at any speed up to at least 30 mph.

b. The transducer was to be able to excite and detect special shear waves that make the vertical split head type of defect more obvious and permit the inspection for transverse head defects to be carried out close to the surface of the head.

c. The transducer was to operate on dirty surfaces and especially on lubricated rails.

d. Since the transducer's orientation relative to the rail surface was not very critical to the ultrasonic beam trajectory, very simple transducer support structures were to be used.

These requirements and some of the equipment developed under this early development program formed the principal basis for the work described in the present report which focused on bringing the equipment into a mode of on-track study, data gathering and system analysis.

3.0 OBJECTIVE

The objective of the program described in this report was to translate the conceptual designs and single transducer operations developed previously into a field worthy prototype system capable of sustained field testing. In this way, a realistic comparison with conventional flaw detection systems under actual field conditions could be carried out. A second, major objective is to clearly demonstrate the advantages of EMAT rail flaw detectors in order to facilitate deployment of such systems within the rail industry. Furthermore, the resulting vehicle could ultimately provide the Transporation Test Center in Pueblo, Colorado with an enhanced rail flaw detection capability.

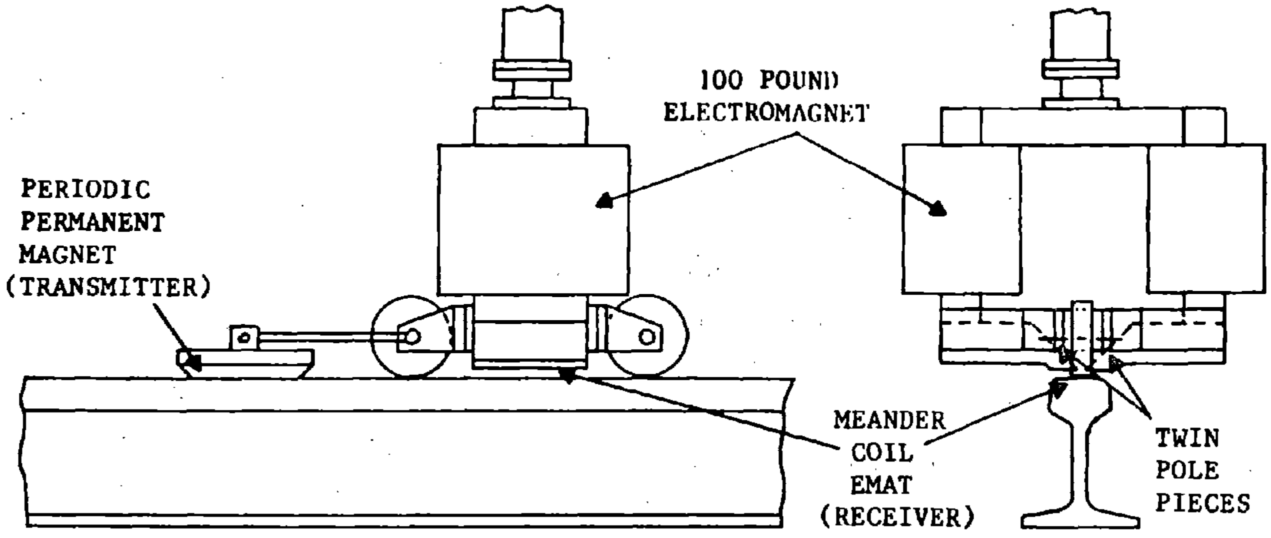
4.0 INSPECTION VEHICLE DESIGN

4.1 TRANSDUCER DESIGN

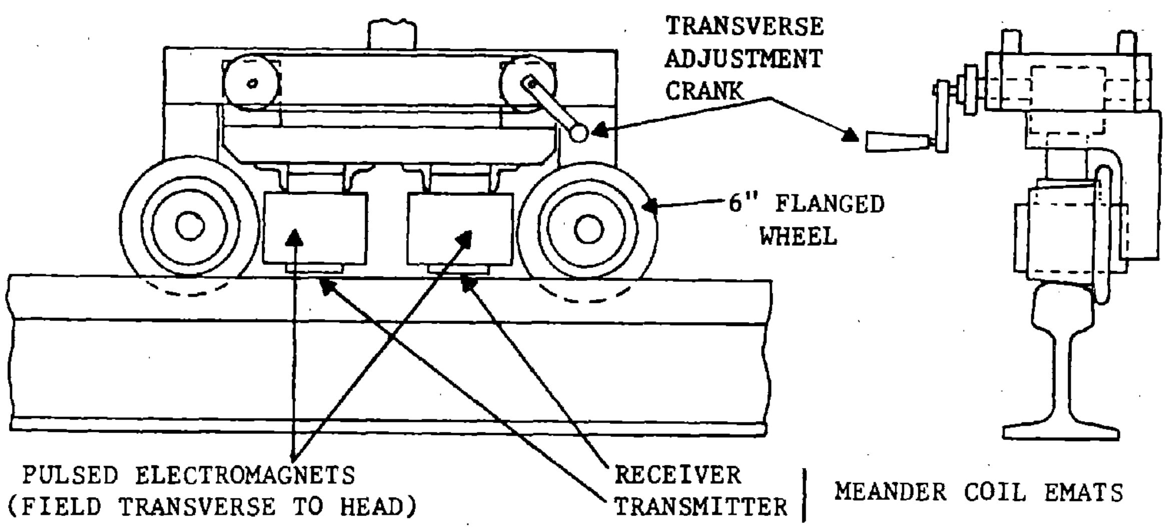
The basic element in the design of a field worthy inspection vehicle is the use of the Electromagnetic Acoustic Transducer or EMAT[4] that can perform an ultrasonic inspection without any liquid couplant and is capable of utilizing new and unusual types of shear waves.[5,6] It consists primarily of a coil of wire that rests lightly against the rail head and a magnet to magnetize the metal under the coil. By controlling the direction of the magnetic field and the geometry of the windings in the coil, either longitudinal or shear type ultrasonic waves can be excited or detected and their direction of propagation can be chosen. Two separate magnet and coil systems were chosen for the rail inspection vehicle in order to separate the inspection of the head and the web of the rail. These two transducer systems are referred to as the 0° EMAT and the 90° EMAT because the former uses a shear wave that propagates at 0° to the surface normal of the rail head while the latter sends its wave along the head at an angle of 90° to the surface normal.

4.1.1 90° EMAT System

In the experimental system used by Rockwell International for their early research work, the transmitter and the receiver EMATs in the 90° system were of fundamentally different design. The transmitter was a compact array of permanent magnets while the receiver required a large electromagnet to suppress Barkhausen noise. Both transducers operated on the same kind of shear wave called a Shear Horizontal or SH wave because it shears the metal in the plane of the surface. Rockwell showed that this particular type of wave could skim along just under the surface and reflect strongly from transverse flaws that lay close to the surface even though the rail surface may be covered with small cracks or checks that reflect the Shear Vertical or SV waves used by conventional transducers. The top drawing in Fig. 1 shows the Rockwell 90° EMAT configuration with a small periodic permanent magnet[7] transmitter and a massive electromagnet receiver.[8] Although the transmitter is compact and quite efficient, it cannot be used as a receiver in a moving inspection system because the motion induced Barkhausen noise generated by the permanent magnets obscures the small ultrasonic signals. Furthermore, the mass of the electromagnet combined with the magnetic force of attraction with the rail demanded that steel wheels be used and these introduced additional noise signals when the transducer moved on dirty rails and at speeds exceeding 3 mph. In order to improve on the Rockwell design and thus overcome the speed and noise limitations, Magnasonics introduced a third EMAT design that utilized magnetostrictive



ROCKWELL SH WAVE SYSTEM



MAGNASONICS SH WAVE SYSTEM

Figure 1. Schematic diagrams of the Rockwell and Magnasonics 90° EMAT configuration drawn to the same scale.

coupling[9] instead of the Lorentz[4] force between a magnetic field and a surface current. The consequences of using this approach are shown on the bottom of Fig. 1 where it can be seen that the use of small, pulsed electromagnets for both the receiver and the transmitter reduced not only in the overall dimensions but also the total mass of the transducer system. In addition to these reductions in the size and weight of the transducers, the magnetostrictive mechanism allowed some additional improvements to be introduced. These were: (1) the EMAT coils could be made less sensitive to the thickness of the air gap under the coil and hence, could better accommodate dirty and lubricated rails; (2) they could be operated at higher frequencies where mechanical noises produced by wheels rolling on dirt were not so severe; (3) the transmitter EMAT did not have a magnetic force that pressed the EMAT tightly against the rail and hence would have a longer wear life and (4) by using higher frequencies, the sensitivity to small transverse defects is greatly enhanced.

For all of these reasons, the Magnasonics system was designed to operate through the magnetostrictive mechanism at 500 kHz instead of the 250 kHz frequency used by Rockwell. Both the transmitter and receiver EMAT coils were mounted on compliant supports to better track irregular rail heads and to have longer wear lives. Fig. 2 shows a drawing of the 90^0 EMAT coils which fit between the pole pieces of the electromagnet such that the field is parallel to the long wires in the meander line and perpendicular to the rail length.

One drawback to using magnetostriction is that the transduction efficiency may vary widely from rail to rail along the track because cold work in the rail head and alloy compositions with high chromium content are known to exhibit lower magnetostrictive coupling coefficients. Early in this program, a study of the magnetostrictive efficiency and hence the sensitivity of the 90^0 EMATs was conducted on 36 rail samples available to Magnasonics and the histogram shown with the solid line in Fig. 3 was developed. The dashed line histogram was taken from Figs. 6-17 of the Rockwell report and is based on efficiency measurements made with their Lorentz force EMATs using a short section of the Santa Fe Railroad test track. The relative position of the maxima in these two histograms is not well defined because it depends on an estimate of the absolute efficiencies of the two methods of generating

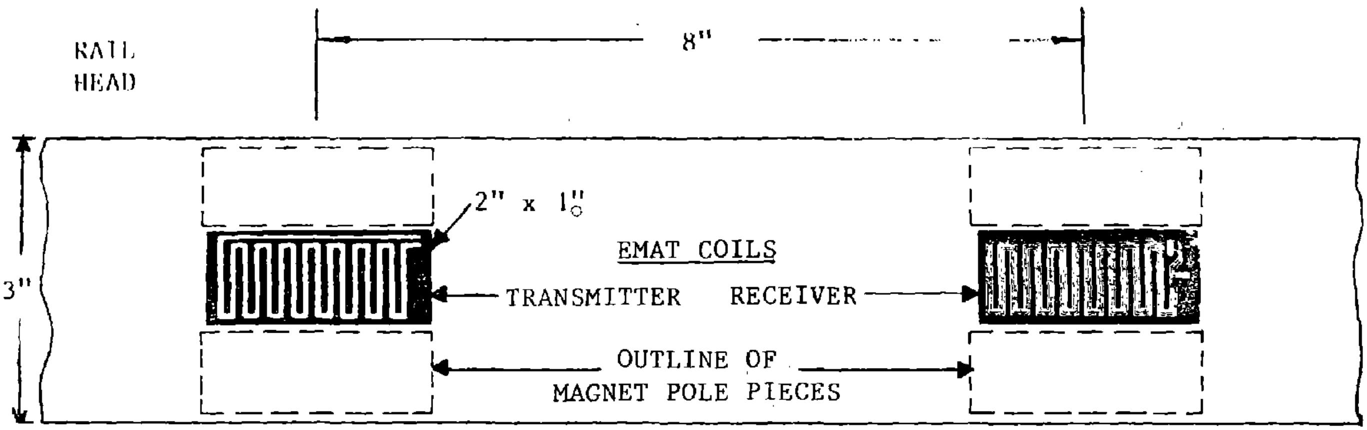


Diagram showing the 90° EMATs positioned for rail head inspection.

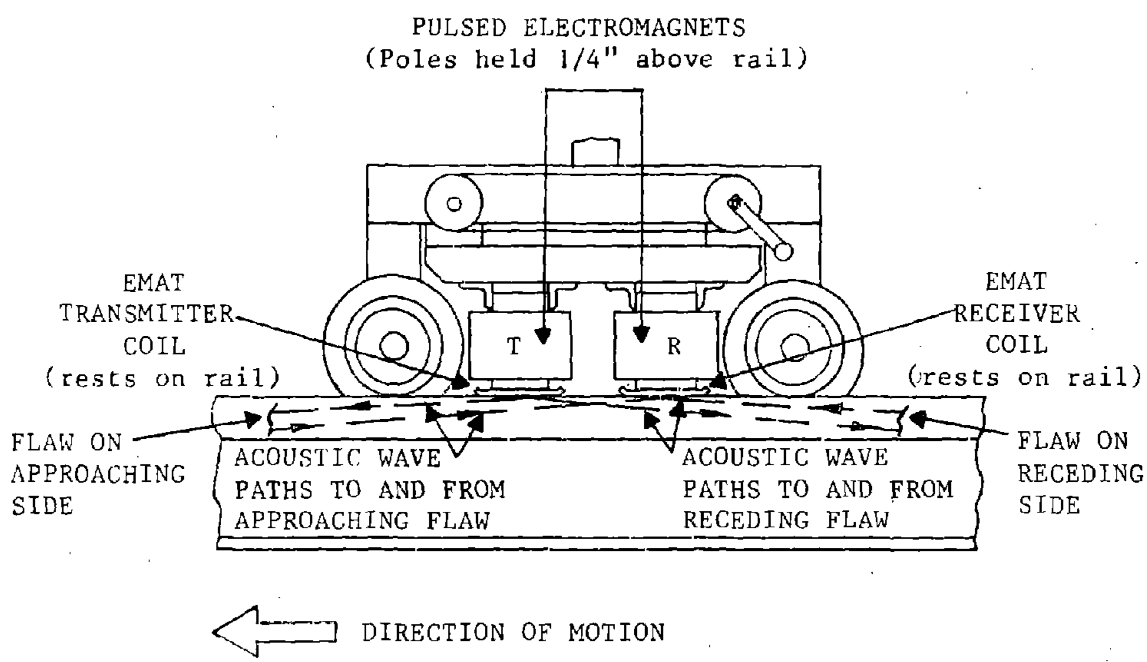


Figure 2. EMAT coils (top) and magnet carriage (bottom) used for the 90° inspection system.

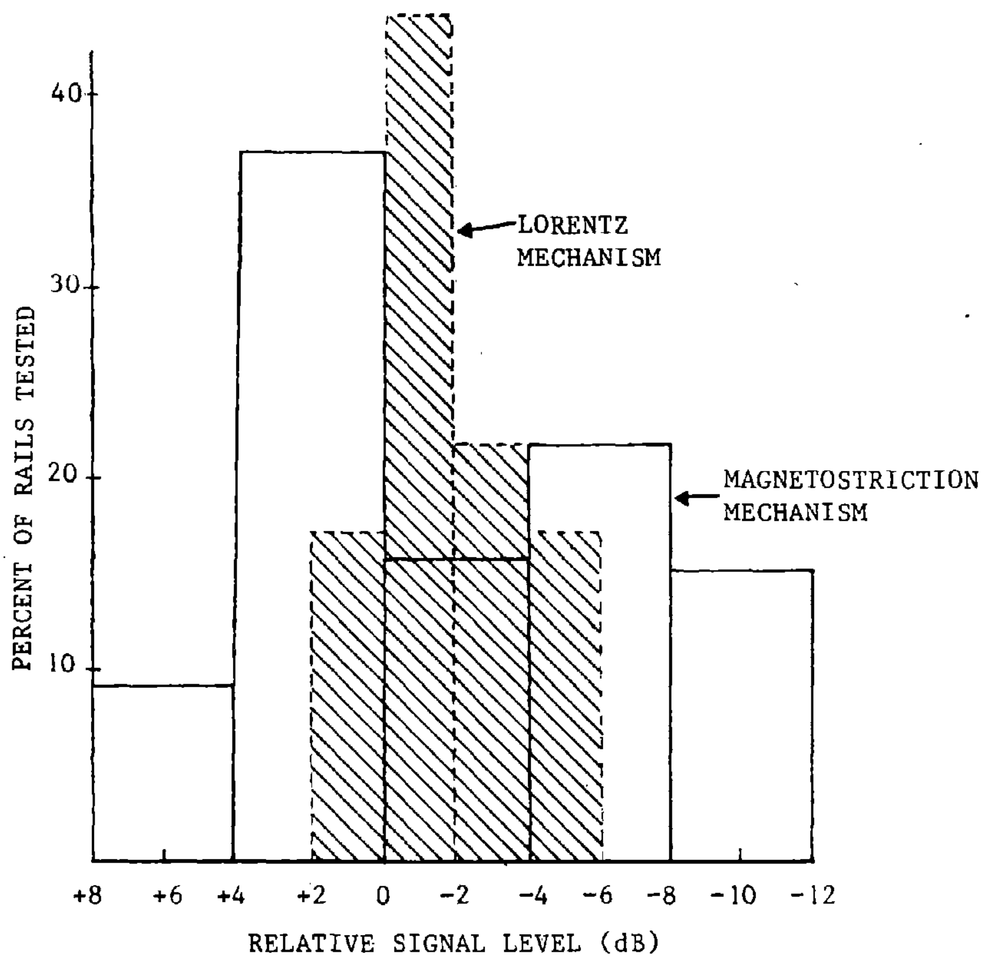
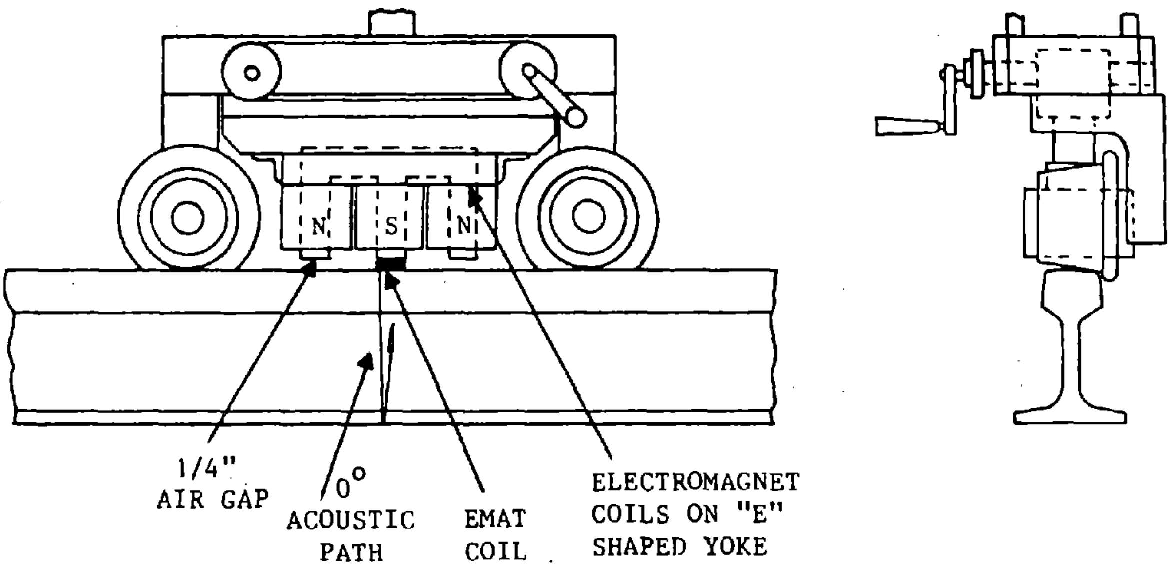


Figure 3. Histograms showing the distributions in efficiency for the magnetostriction mechanism and the Lorentz mechanism on the 32 sample rails containing defects.

SH waves. However, the magnetostrictive mechanism exhibited a higher absolute efficiency and, even though the histogram shows a wider range of efficiencies, it was felt that this inherently higher efficiency would make up for the low efficiency on a few rails.

4.1.2 0° EMAT System

For the Rockwell experiments, the bulky electromagnet shown in the top drawing of Fig. 1 was used. For the Magnasonics inspection vehicle, this magnet was judged too large to accommodate frogs and switches so a smaller, more efficient magnet was designed. A drawing of this magnet is shown in Fig. 4 along with the EMAT coil used to excite and detect the 0° shear waves. These waves enter the rail head perpendicular to the surface of the head and propagate through the web to the base where they are reflected back to the head and the EMAT that introduced them. As shown in Fig. 4, the EMAT coil is actually a side-by-side, transmitter/receiver pair of coils that is sandwiched between the magnet pole piece and the head of the rail where the magnetic field is nominally perpendicular to the surface of the head. Theoretically, no magnetostriction is involved in the efficiency of this EMAT and the signal strength or efficiency should vary as the square of the magnetic field in the gap. Unfortunately, and in agreement with data shown by the Rockwell International studies, this quadratic dependence was not exactly followed and the general level of efficiency was found to be smaller in worn rails. These empirical facts are shown in graphical form in Fig. 5 where the dashed lines have the parabolic shape predicted by theory. For the tests in the field, the magnetic field was kept as high as possible but the efficiency still varied from rail to rail as more or less wear was encountered. Data on the actual efficiency variations encountered in the field was obtained with the final system on Section 10 of the Facility for Accelerated Service Testing (FAST) track in Pueblo, Colorado. These data are shown in histogram form in Fig. 6 where it can be concluded that the width of the distribution in efficiency for the 0° EMATs which operate through a Lorentz force coupling mechanism is very similar to the distribution observed for the magnetostrictive mechanism shown in Fig. 3 which was used for the 90° EMATs. No explanation for this similarity is available at this time.



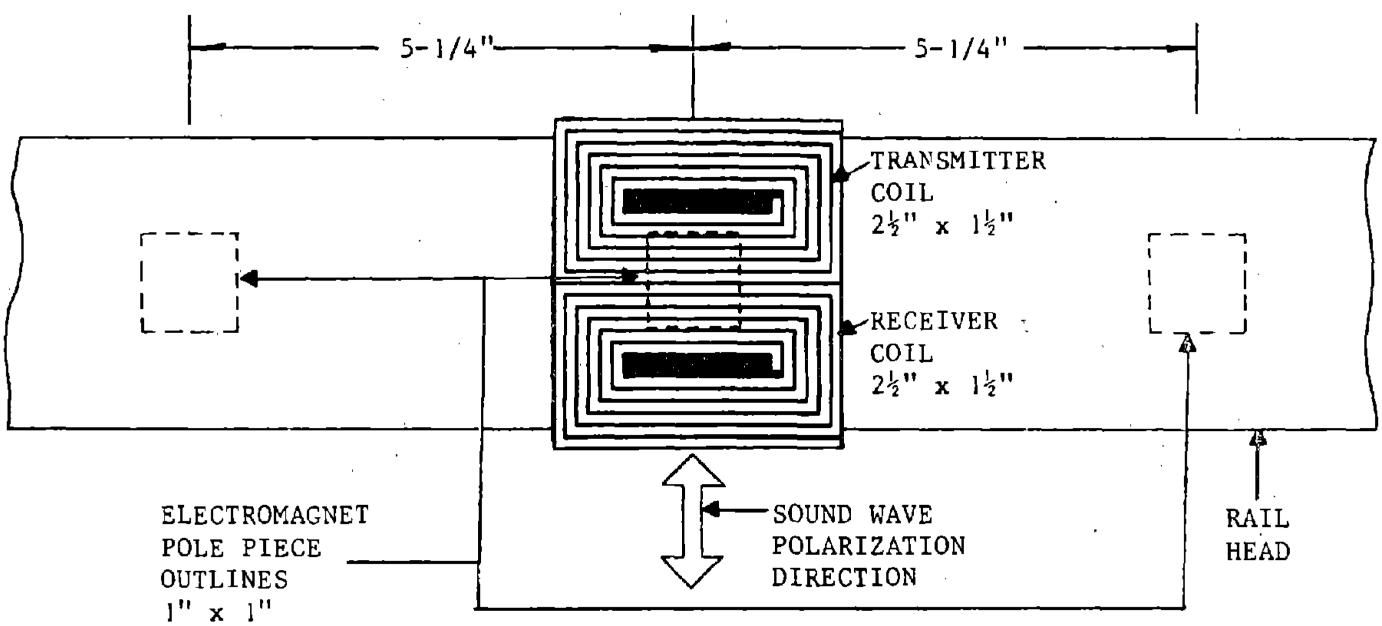


Figure 4. Drawing of the dc electromagnet carriage (top) and the EMAT coil (bottom) configuration used for the 0° EMAT that inspects for defects in the web by reflecting sound from the base.

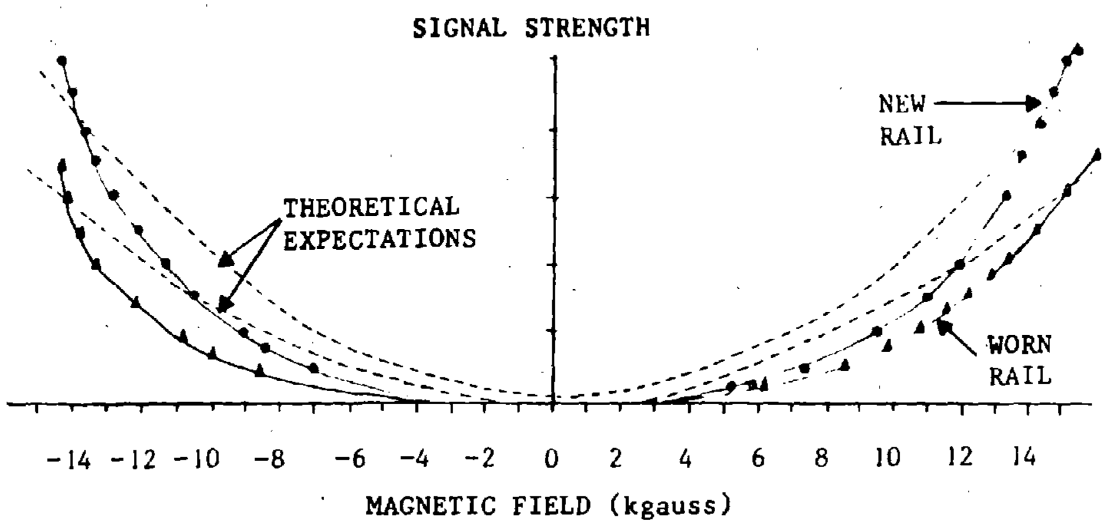


Figure 5. Efficiency of the 0° EMAT (Lorentz mechanism) as a function of magnetic field in the gap under the dc electromagnet used on the inspection vehicle.

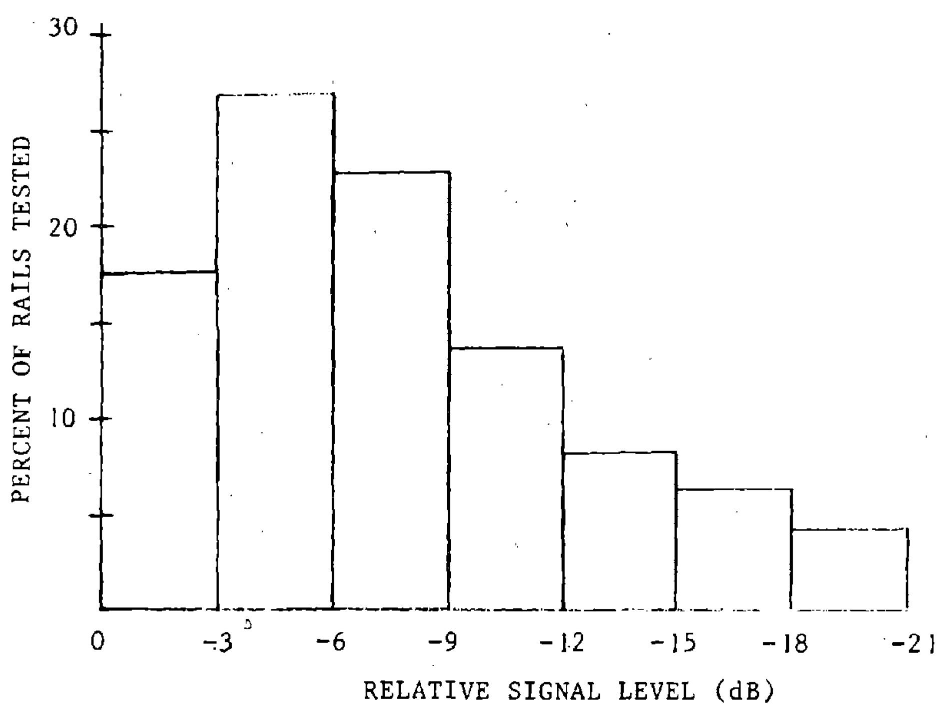


Figure 6. Histogram of the efficiency of the 0° EMAT operating on Section 10 of the TTC test track.

The primary use of the 0° EMAT was to detect flaws in the web of the rail by observing when the reflection from the base was abnormally attenuated. It was also found by the Rockwell International studies that if the shear wave produced by the 0° EMAT was polarized perpendicular to the web, then a vertical split head type of defect produced a maximum change in the amount of attenuation and thus was most effectively detected. Magnasonics used its 0° EMAT to verify this observation and to study the phenomenon at different frequencies. Fig. 7 shows the results of this study on rail samples with various amounts of head wear. Although the vertical split head (VSH) defect usually caused a large drop in reflected signal at the frequency of 2 MHz used by Rockwell, a lower frequency of 1.5 or 1.0 MHz would make the effect more pronounced and hence make the detection of this defect more reliable. Whenever the next series of improvements are introduced into the inspection system, it is recommended that the operating frequency of the 0° EMAT channel be lowered from its present 2 MHz to 1 MHz.

4.2 TRAILER DESIGN

Early in this program, a design review team composed of representatives from Sperry Rail Service, the AAR, the Santa Fe Railroad, Rockwell International and the FRA was assembled at Magnasonics, Inc. in Albuquerque, New Mexico, to discuss detailed mechanical design criteria for the inspection vehicle. The following list summarizes their recommendations.

1. The EMAT coils should have a compliant backing and a wear resistant face to ride lightly on the rail head and track minor variations in the orientation of the surface. Sufficient clearance and shock resistance should be available to accommodate a 1/4" step at a rail joint.

2. The coil and magnet structure should be supported on wheels with flanges so that the EMAT would follow a path at a fixed distance from the gage face of the rail head. A crank should be available for the operator to adjust this distance in the field.

3. Each individual EMAT carriage (two at 90° and two at 0°) should be retractable for off-rail transport and free enough to ride over obstacles

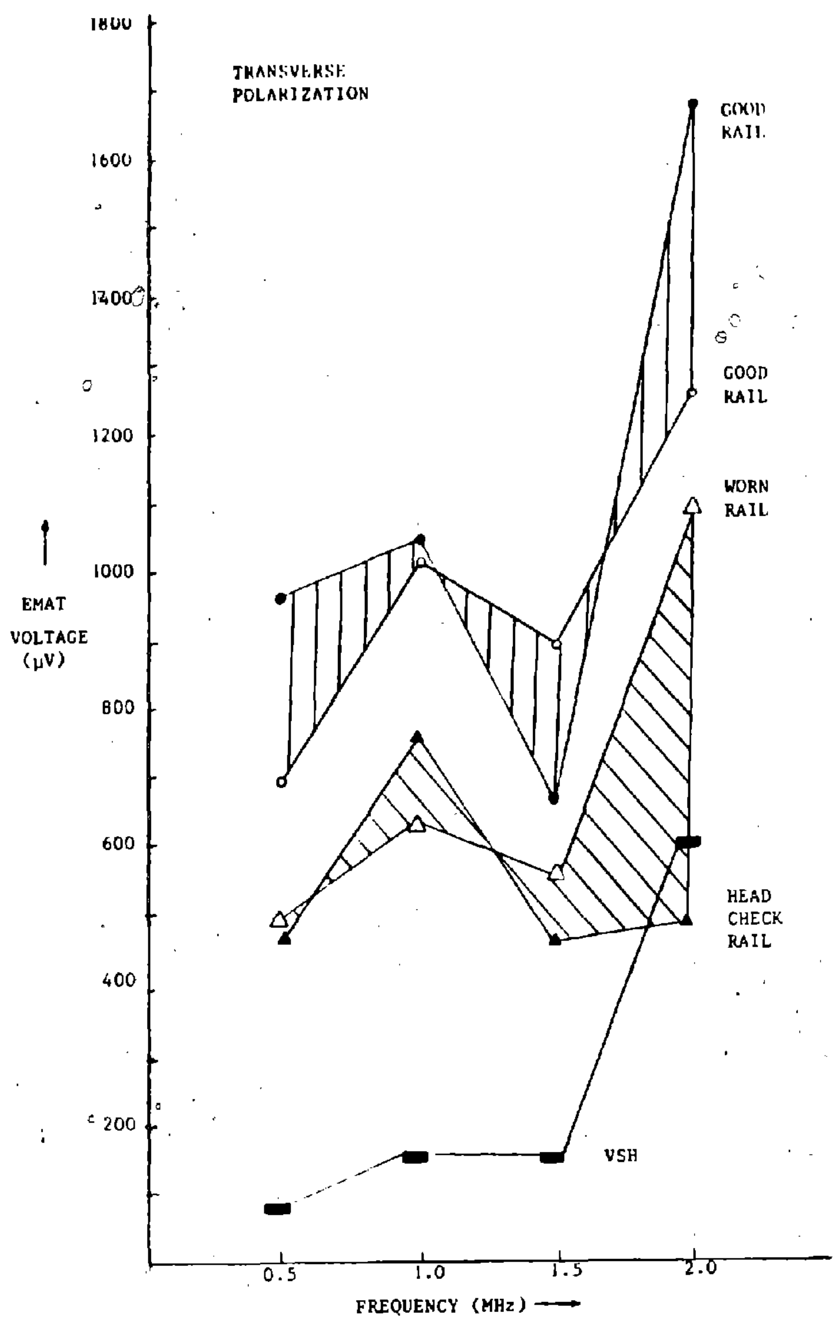


Figure 7. Dependence of the base reflection signal in the 0^{o} EMAT channel on the frequency of operation and the amount of wear on the head of the rail. Case of the shear wave polarized perpendicular to the plane of the web.

on the rail while in the inspection position. Each should be sized to be able to pass through frogs and switches.

4. The frame that supports the EMAT carriage should be a trailer capable of being towed on a highway or on railroad tracks, i.e., a highway-rail type of trailer. It must have sufficient strength to support all the parts so that the vehicle can be totally self-contained.

Fig. 8 shows the basic design of the trailer frame. It consists of a central box structure to support the two rubber highway wheels and their axle. This box is equipped with a hand crank and lifting screws that raise and lower it relative to the main frame of the trailer. Four 10" diameter, flanged railroad wheels support the main frame when it is on the railroad tracks. The diameter and the flange dimensions of these wheels were chosen to allow the trailer to be pushed backwards around a 20 degree curve at 25 mph.

Fig. 9 is an outline drawing of the assembled inspection trailer showing the EMATs in position to inspect the rail. Its most significant loads are the power supply motor generator set and the instrument box. The former is the heaviest object and hence is positioned over the highway wheels. The latter is located such that the trailer nearly balances on its highway wheels. In this way, the trailer may be maneuvered from the highway onto the rails at a road crossing by small forces on the tongue of the trailer. This tongue force, however, must be large enough to insure a firm connection to the towing vehicle under normal operation. Thus, in the final design, all the components on the trailer are located to make this force about 250 pounds or between 5 and 10 percent of the trailer weight.

In order to make the system completely self-contained, the instrument box was designed to hold all of the individual chassis boxes needed for the electronic data processing and display. However, during actual field operation, some of the boxes are to be carried on the towing vehicle so these have been equipped with long cables and connectors to allow the system to be operated from a location about 20 feet away.

The mechanical system also included hydraulic pumps, valves and hoses for raising and lowering the EMAT carriages and for maintaining the EMAT

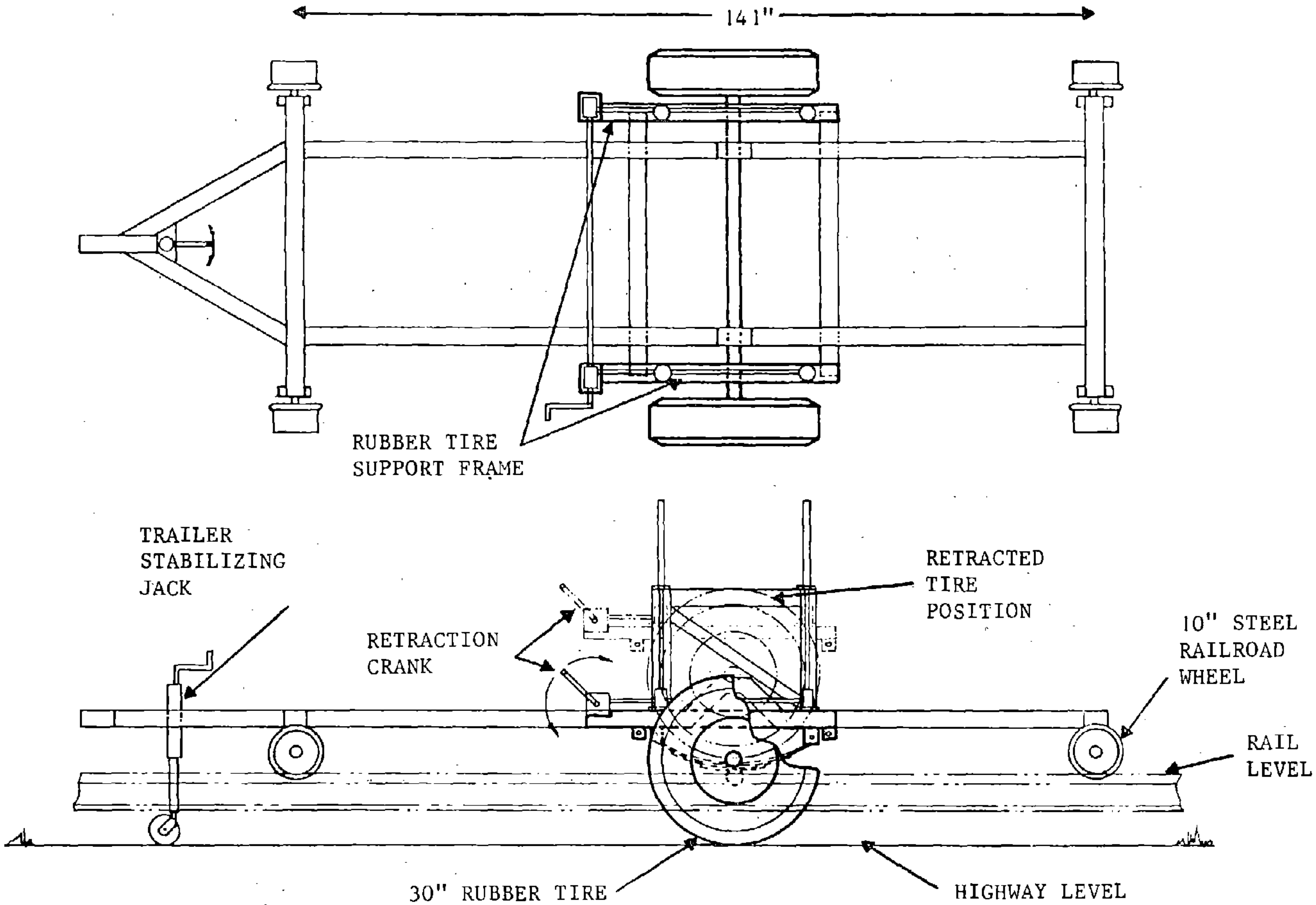


Figure 8. Basic frame of the inspection trailer.

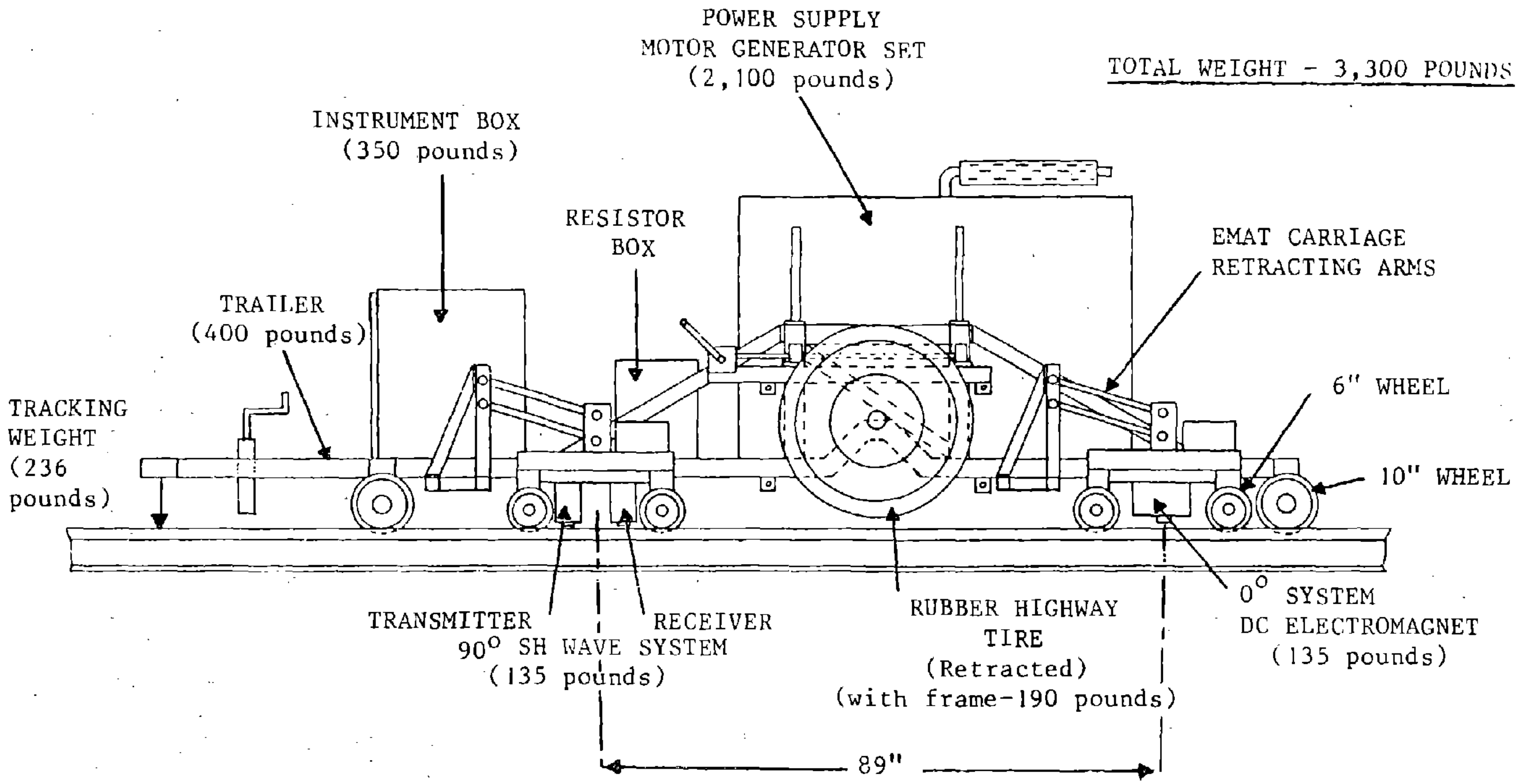


Figure 9. Outline drawing of the complete trailer positioned on rails ready for a single rail inspection. The important weights and dimensions are shown with each of the main components.

carriage wheels pressed against the gage side of the rails. Control of this hydraulic system was not extended to the towing vehicle but must be done by the operator while standing beside the trailer. Power for the 1500 psi, 1 gpm hydraulic pump was supplied by the 12 volt battery in the main motor generator set.

4.3 POWER SUPPLY DESIGN

The EMAT magnets require the most power and hence dominate the specifications for the on-board power supply. Since the pulsed magnets demand a dc source to maintain a charge on their capacitor banks and the 0° EMAT electromagnet used only dc power, the most efficient choice was a portable motor generator set designed for dc arc welding. Commercial units for this use are equipped with an auxiliary, 110 volt ac output so the electronic circuits of the EMAT system did not need any special source for their power. The power requirements for each subsystem are listed below.

1. 90° EMAT, 2 coil pulsed electromagnet----------- 2 kVA
2. 0° EMAT, 1 coil dc electromagnet---------------- 0.2 kVA
3. Electronics (110 volt, ac)---------------------- 1 kVA

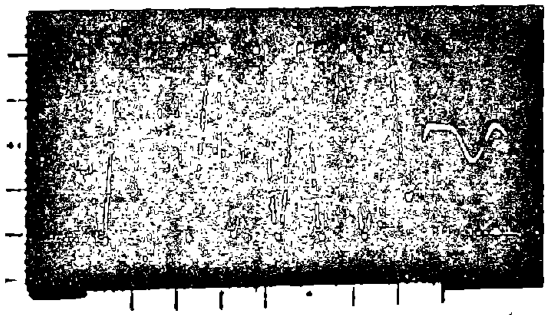
Thus, the inspection of two rails will require a minimum of 4.4 kVA of dc power. To get the desired dc voltage level and good control over the stability of the output, a Miller "Big 40" Arc Welder unit which can produce 8 kVA of output was chosen. It operates on gasoline and has a 3 kVA ac output which easily supplied the requirements of the electronics.

4.4 ELECTRONIC DESIGN

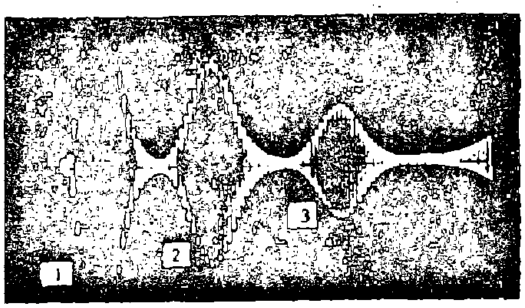
4.4.1 Analog Signal Processing

The basic inspection procedure consists of forming an RF tone burst, converting it into an ultrasonic wave in the rail, reconverting any received signals into electrical signals, amplifying and rectifying these signals, passing them through a series of time windows and finally storing a voltage proportional to the maximum signal in each time window on an array of sample-and-hold circuits where the digital computer could have access to the information when needed. In an EMAT system, the application of the tone burst signal to the EMAT transmitter coil requires a unique, high current amplifier circuit and the preamplifiers connected to the receiver EMAT coils must have low noise characteristics when connected to low impedance inductances. Both of these critical circuits were developed by Rockwell International during the research phase and were used in this contract with only small modifications. Examples of some typical electrical signals in the 90^{o} EMAT channel are shown in Fig. 10. Circuits for forming the windows and for charging the sample-and-hold circuits are common to most ultrasonic systems so they only needed packaging and installation in the Magnasonics Central Control Box carried in the inspection vehicle.

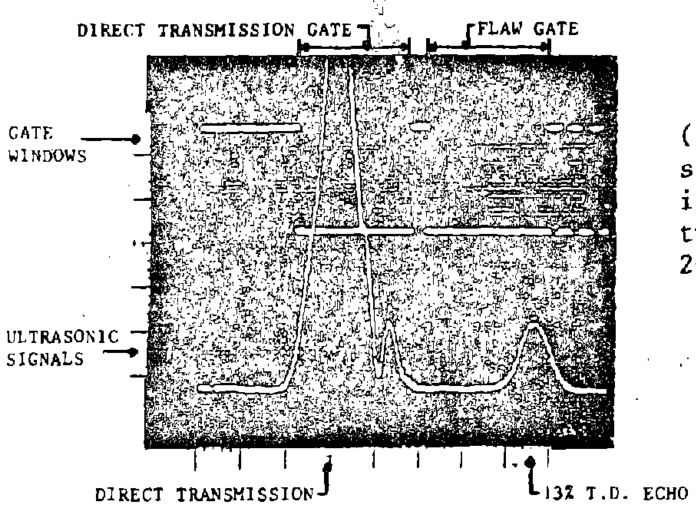
One feature of EMATs that was used in the Rockwell International studies and essentially copied by Magnasonics was the use of two receiver coils under the 90^{o} EMAT pulsed electromagnet. By positioning the two coils 1/4 wavelength apart and combining their outputs in a phase shifting network, it was possible to distinguish between ultrasonic waves that approached the EMAT from the right and from the left. Application of this feature to rail inspection allowed utilization of the fact that a single 90^{o} transmitter produces two ultrasonic outputs; one being an acoustic signal that propagates forward and the other, backwards. If the forward going wave reflects from a flaw in front of the EMAT pair, the echo signal will enter the receiver from points ahead or approaching the EMAT while the backward traveling wave will create echoes from flaws from behind or receding from the EMAT. Thus, by monitoring the two outputs from the phase shifting network, a given flaw in the head of the rail will produce echo signals that are first detected as the EMAT approaches the flaw and then detected again as the EMAT recedes from the flaw. This not only increases the probability of detection but by comparing the amplitudes of the echoes in the two channels, it is possible to gain information on the orientation of the defect. As a result of implementing this directional feature of EMATs, the output analog signal processing circuits are designed to handle three channels of information from a single rail: one for the 0^{o} echoes, another for the 90^{o} approaching echoes and a third for the 90^{o} receding



(a). Transmitter current tone burst. (20 amps/div. vertical; 2 μsec/div. horizontal)



(b). RF output of the 90° EMAT receiver showing three signals. No. 1-the feed-through signal when the transmitter is operating. No. 2-the ultrasonic signal received directly from the transmitter (called the Direct Transmission signal). No. 3-an ultrasonic echo signal returned from a rail end. (2 volts/div. vertical; 20 μsec/div. horizontal)



(c). Detected version of the RF signals shown above except that the echo signal is from a 13 percent transverse defect type of flaw. (1 volts/div. vertical; 20 μsec/div. horizontal)

Figure 10. Oscilloscope photographs of typical signals in the EMAT inspection system. Here, the RF signals have been passed through a fixed, band pass filter with a ± 5 percent bandwidth.

echoes. Thus, the digital signal processing and the display procedures have six channels of information to process at each measurement point along a pair of railroad tracks.

The only special feature that distinguished the Magnasonics analog circuits from Rockwell International was the addition of pulsed magnets to the 90° EMAT system. Fig. 11(a) shows a diagram of the SCR circuit used to supply pulses of current to the electromagnets used for the 90° EMAT and Fig. 10(b) shows a graph of the current waveform. Under typical conditions this circuit is triggered 1300 microseconds before the EMAT transmitter was activated and the pulse duration of 2000 microseconds was chosen long enough to insure that a high magnetic field was always present at the EMATs during the 300 microseconds needed for the ultrasonic waves to propagate in front and behind the sensors by about 10 inches.

4.4.2 Timing and Multiplexing

Since the EMAT inspection system uses shear type ultrasonic waves that travel with a speed of 0.127 in/μsec, it takes the 0° EMAT about 115 μsec to complete its inspection of the web. By allowing 200 μsec for the 90° EMAT system, an inspection of the head of the rail for a distance of nine inches in front of the transmitter and nine inches behind the receiver can be carried out. Thus, a minimum of 315 μsec must be allocated to the ultrasonic part of the inspection of each rail. By allocating 685 μsec for the digital processing of the data, two measurements on a rail can be completed in one millisecond and each transducer can operate at a one kilohertz repetition frequency. Such a rate could cause the pulsed magnets on the 90° system to draw excessive power but since these sensors naturally inspect a considerable distance along the rail with each firing, they were allowed to fire much less often than the 0° EMATs.

In the initial specifications of the inspection vehicle, an odometer wheel was required to trigger the EMAT firings so that the data would be collected and stored on a distance basis rather than on a time basis. To meet these requirements, an odometer wheel with a 24 inch circumference (a 7.64 inch diameter) was attached to an encoder that generated 128 counts per

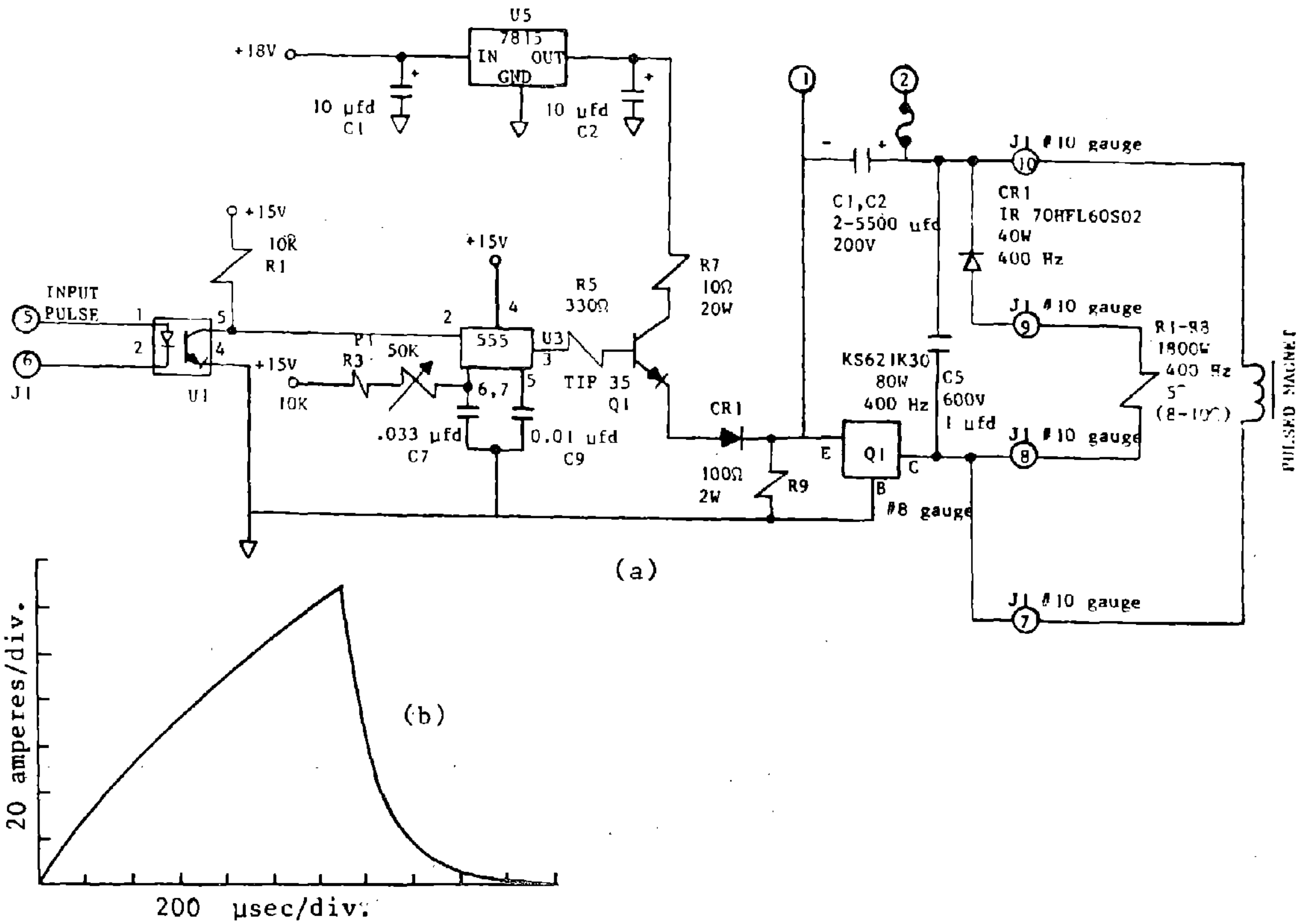


Figure 11. (a) Diagram of the circuit that supplied pulses of current to the 90° EMAT pulsed electromagnets. (b) Drawing of the pulsed current waveform.

revolution. This assembly, therefore, produced a trigger signal every 0.19 inch of motion along the rail. Since the fastest repetition frequency that could be allowed was 1 kHz, the top inspection speed was therefore 190 inches/second or 10.8 mph. Note that although EMATs are able to operate at higher speeds, this top speed of inspection for this EMAT system was set by the data processing speed.

Fig. 12 displays all of these timing constraints in the form of a timing diagram. At time zero, a trigger signal from the odometer wheel or from an internal clock fired the 0° EMAT and opened a window that would label any echo signals received as coming from defects in the web of the rail. Just before the arrival of the reflection from the base of the rail, this window was closed and a window in a second channel was opened to bracket the base echo and thus label the signal in the second window channel as the base echo. In the subsequent 500 µsec, the maximum signal amplitude in each of these windows was stored on a sample-and-hold circuit for the system computer to interrogate, digitize and store in its memory along with the odometer count associated with the initial trigger signal. After about 500 µsec, the 90° EMAT was fired and different windows were opened in both window channels. A multiplexing circuit connected window channel 2 to the output of the phase sensing circuit that produced echoes from the receding side of the 90° EMAT receiver and connected window channel 1 to the output of the approaching side of the 90° EMAT receiver. Two consecutive windows in channel 1 collected first the large signal from the transmitter as it passed under the receiver EMAT on its way along the rail head and labeled it as the "Direct Transmission" signal. The signals in the subsequent window of channel 1 were labeled "Approaching Echoes" because they entered the receiver from the approaching side of the EMAT. The echo signals detected in window channel 2 were labeled "Receding Echoes" because they entered the receiver from the receding side of the EMAT. Again, the maximum signal voltages in each of these windows was stored on sample-and-hold circuits until the computer could collect them and store them in its memory. At 1000 µsec, the 0° EMAT was fired again and the same windowing sequence that accompanied the first firing of the 0° EMAT was repeated. However, this time it was not followed by a 90° EMAT firing so

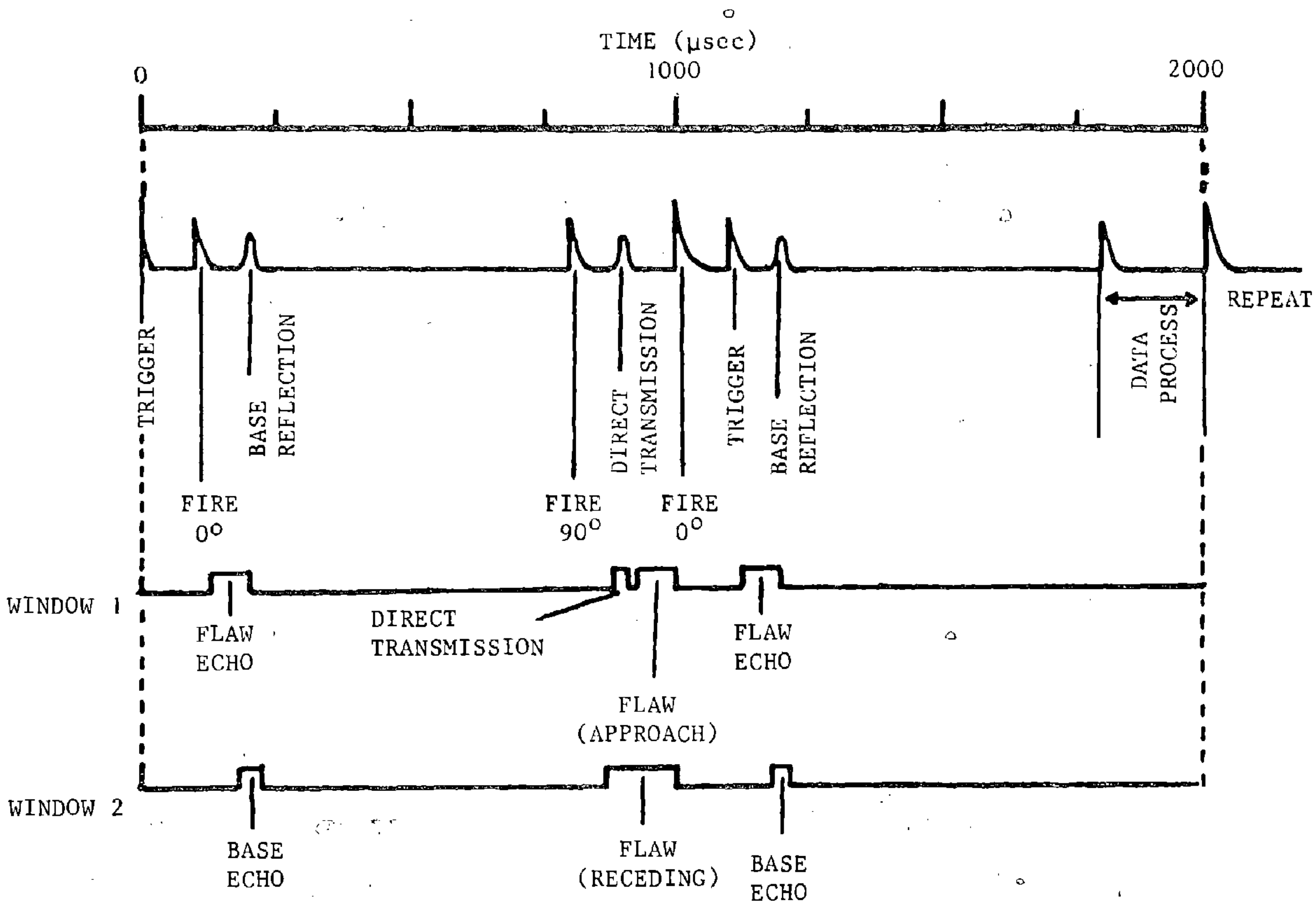


Figure 12. Timing diagram that describes the sequence of triggers and windows used for the inspection of a single rail.

that the pulsed electromagnets could rest and the "free time" could be spent on additional data processing needed to display the data points on a CRT screen or on a strip chart recorder.

4.4.3 Digital Data Processing and Display

As a result of the real time, analog signal processing with windows and sample-and-hold circuits, the computer memory was filled with many individual lines of data—one line for each measurement. Each line contained the following information for a given location along the rail: (1) an odometer count; (2) the maximum echo amplitude from reflectors in the web; (3) the amplitude of the echo from the rail's base; (4) the amplitude of the Direct Transmission signal in the 90° EMAT channel; (5) the maximum echo signal from the receding direction of the head; (6) the maximum echo signal from the approaching direction; (7) a second maximum signal amplitude from the web and (8) a second base reflection amplitude. The odometer count was allocated three bytes because it must be capable of representing a long distance. Each of the signal amplitudes was allocated a byte so that a maximum signal of 10 volts could be represented by 256 units of 40 millivolts each. Once stored in memory, these data could be displayed to an operator in real time or kept for subsequent processing at a later date.

Two options for display of all these data were available. One was the CRT of the computer while the other was the strip chart recorder. The former is fast enough to keep up with the data collection rate of seven signal amplitudes for each odometer pulse but it is difficult for a human operator to react to all this information on a continuous basis. The latter is easier for the operator but its response time is too slow to record the results of each triggering signal from the odometer wheel. Thus, the first signal processing task of the computer was to perform an elementary screening of the data for presentation on a strip chart. This consisted of grouping the data into sets of ten readings and sending the largest signal amplitude in the set on to the recorder. To further simplify the display, this largest signal amplitude was compared with an operator-set threshold level and if the echo exceeded this threshold, the pen of the recorder was moved to a deflection proportional to the amplitude. This procedure accommodates the slow response of the recorder and also allows the pen to "map" the amplitude variations as a function of the position along the rail if the flaw extends over an appreciable distance. In addition to this flaw information, the combined computer/recorder technique provided a means for monitoring the quality of the inspection by displaying the ultrasonic transducer efficiency at each point. This was accomplished by using a two channel strip chart recorder and deflecting one pen in proportion to the amplitude of the direct transmission signal in the 90° EMAT channel and the other pen in proportion to the amplitude of the signal reflected from the base of the rail in the 0° EMAT channel. Under ordinary conditions on a good rail, the two pens mark out a path near the center of the chart. If the transducer's apparent efficiency decreases because a large flaw or a rail end intercepts the 90° sound beam in the head or a bolt hole in the web or a weld bead on the base scatters the 0° beam, the pens move downward to much lower deflections and thus signal the operator of these conditions. If a long section of rail is worn or its head surface is seriously misoriented so that the EMAT does not couple well, then the pen will remain at a low deflection for a long time and the operator can increase the gain of that channel or readjust the position of the sensor on the head. Under all of these conditions, the pen can still be moved to large deflections by flaws that cause echoes thus insuring that flaws are not missed.

Figs. 13 and 14 show some examples of the strip chart records as the EMATs were scanned over sample rails in the laboratory. The top record, Fig. 13, is for a 90° EMAT scanning across a transverse defect in the head of rail sample 319. Here the normal signal level of the flaw-free rail is between 2.5 and 3 divisions. As the EMAT pair approached the defect, a small echo in the approaching channel deflected the pen a few tenths of a division up scale. As the EMAT pair passed over the flaw, the defect intercepted the sound beam and lowered the direct transmission which lowered the deflection of the pen for the entire time that the flaw was between the EMATs. Immediately after the flaw emerged from under the EMATs, a large echo appeared in the receding channel and the pen was deflected by over 5 divisions up scale. Once the flaw had passed the EMATs, the pen returned to the normal position at a 3 division deflection. Therefore, a transverse defect in the head should cause a very

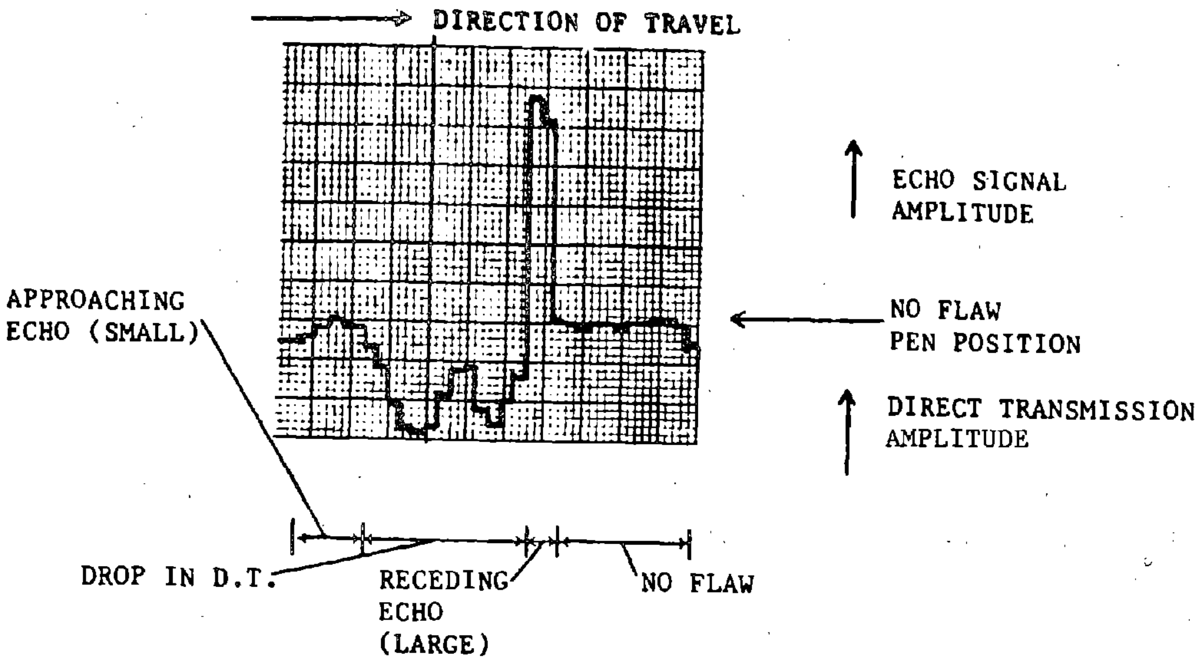


Figure 13. Example of a strip chart recording caused by the passage of a 90° EMAT over a transverse defect in rail sample No. 319 in the laboratory.

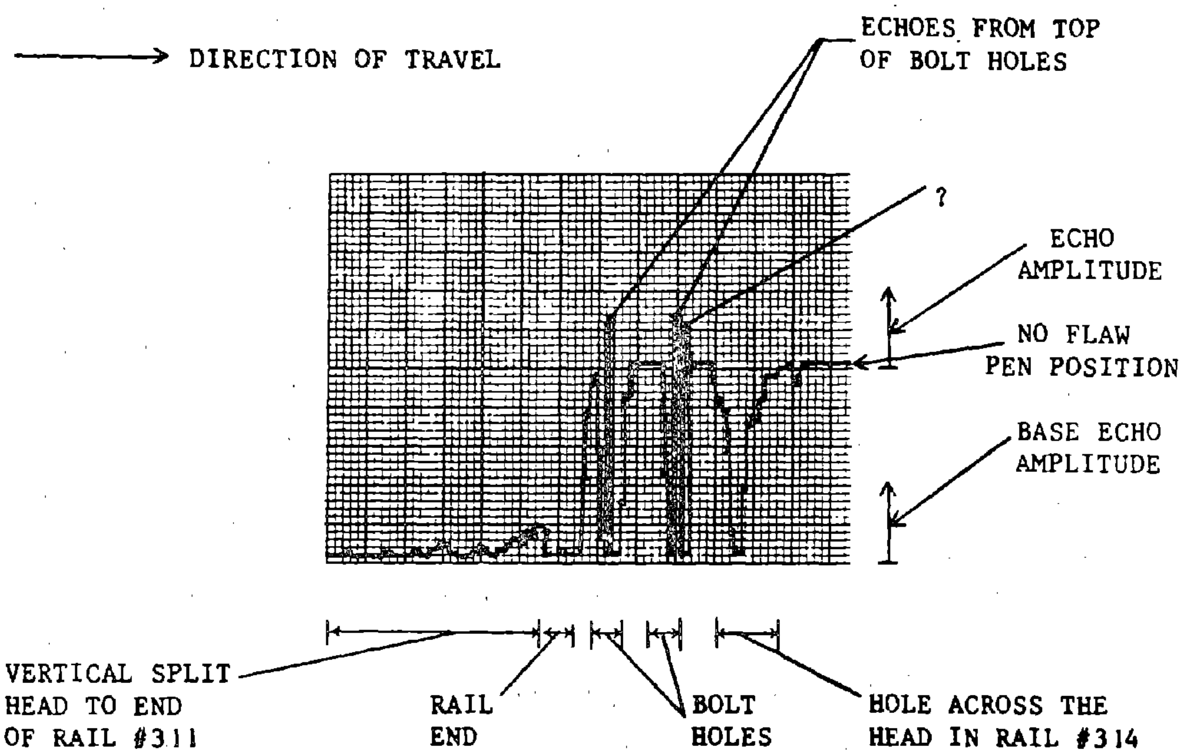


Figure 14. Example of the strip chart record for a 0° EMAT scanning from a vertical split head defect in rail No. 311, across the rail end, and then over two bolt holes and a hole in the head of rail No. 314 in the laboratory.

characteristic signature on the strip chart consisting of two positive deflections with a dip between.

Fig. 14 shows an example of the strip chart record produced when the 0° EMAT was scanned across the joint between two rails. Here, the no flaw position of the pen (corresponding to a good reflection echo from the base) is at midscale and occurs on the right side of the chart. On the left side of the chart, the EMAT was over a vertical split head in rail sample 311. This flaw extended up to the end of the rail which appears in the middle of the chart. Both the vertical split head and the rail end prevent a base echo from being formed and the chart pen registers a very low deflection until the EMAT moves onto rail 314. Two bolt holes in the end of rail 314 appear as sudden decreases in the pen deflection and a third, wider decrease in echo amplitude and pen deflection on the right side of the chart was traced to a hole drilled horizontally across the head of the rail.

In a practical rail inspection, it is common practice to operate at such high gain levels in the amplifiers that the base echo and the direct transmission signals are saturated so that their apparent signal amplitudes do not change as the vehicle moves down the track. Use of such a procedure in this computer controlled system would simplify the strip chart presentation by insuring that the pen would usually draw a straight line down the center of the chart in the absence of flaws in the head and in the presence of a strong reflection from the base. Flaw echoes would deflect the pen upward and complete disappearance of the ultrasonic signal would deflect the pen downward. Clearly, it will be a matter of taste and experience to decide exactly where to set the gain controls and thresholds to present the operator with the optimum amount of information.

The use of the computer to "buffer" the signals to the strip chart recorder not only allows rapidly changing flaw signals to be recorded but it makes possible the presentation of additional, potentially useful information to the operator. However, it does not present all the details in the signals that may be needed to make quantitative judgements concerning the severity of flaws or to distinguish between some similar types of defects. In particular, bolt hole cracks are detected only by the fact that they cause the disappearance of the base echo to extend over an abnormal distance along the rail. An exact measurement of the width of the "shadow" cast by a bolt hole can only be made from a very detailed examination of the width of the zero base echo signal amplitude as a function of location of the 0^{0} EMAT. Since the computer memory actually holds this specific information, a second value of having the inspection system controlled by a computer is the ability to display the details of any signal variation at any time after the EMAT has passed over a questionable area. Fig. 15 is an example of this capability since it shows a detailed graph of the echo amplitude values stored in the computer memory as a function of the location of the 0^{0} EMAT as it scanned along two rail samples labeled rail 219 and rail 32. (These data are much more detailed than usual because they were taken when the system was being triggered by a constantly running clock as would be the case if the inspection was being performed at a very low scanning speed to collect detailed data on a specific region of track.) Rail 219 is noteworthy because it contains three bolt holes in the web and a head-web separation at the left end. The ultrasonic information clearly shows the vanishing of the base reflection over a well defined distance in the vicinity of the two bolt holes on the right and the total lack of a base echo under the head-web separation on the left. Note that there appears to be a reflection from the edge of the separation in the region where the base echo disappears. There are also some small echoes when the EMAT was directly over the bolt holes. Rail 32 shows the bolt hole shadows more clearly and larger echoes from them in the top line of the figure. However, it presents an excellent example of the distortion of the bolt hole shadow by the presence of a bolt hole crack eminating from the left side of the hole. A large echo from the base of the crack, next to the hole clearly appears in the web echo channel.

Fig. 16 shows similar detailed signal amplitude data obtained in rail 303 with the 90^{0} EMAT. Here, the center graph displays the Direct Transmission signal amplitude which was so large that it saturated the amplifier and caused all the data points to plot at the top of the scale with no apparent variations as a function of EMAT position. The large echo amplitude shown on the right end of the approaching echo channel was produced by the transverse defect. Unfortunately, this particular defect appears to have been poorly oriented for

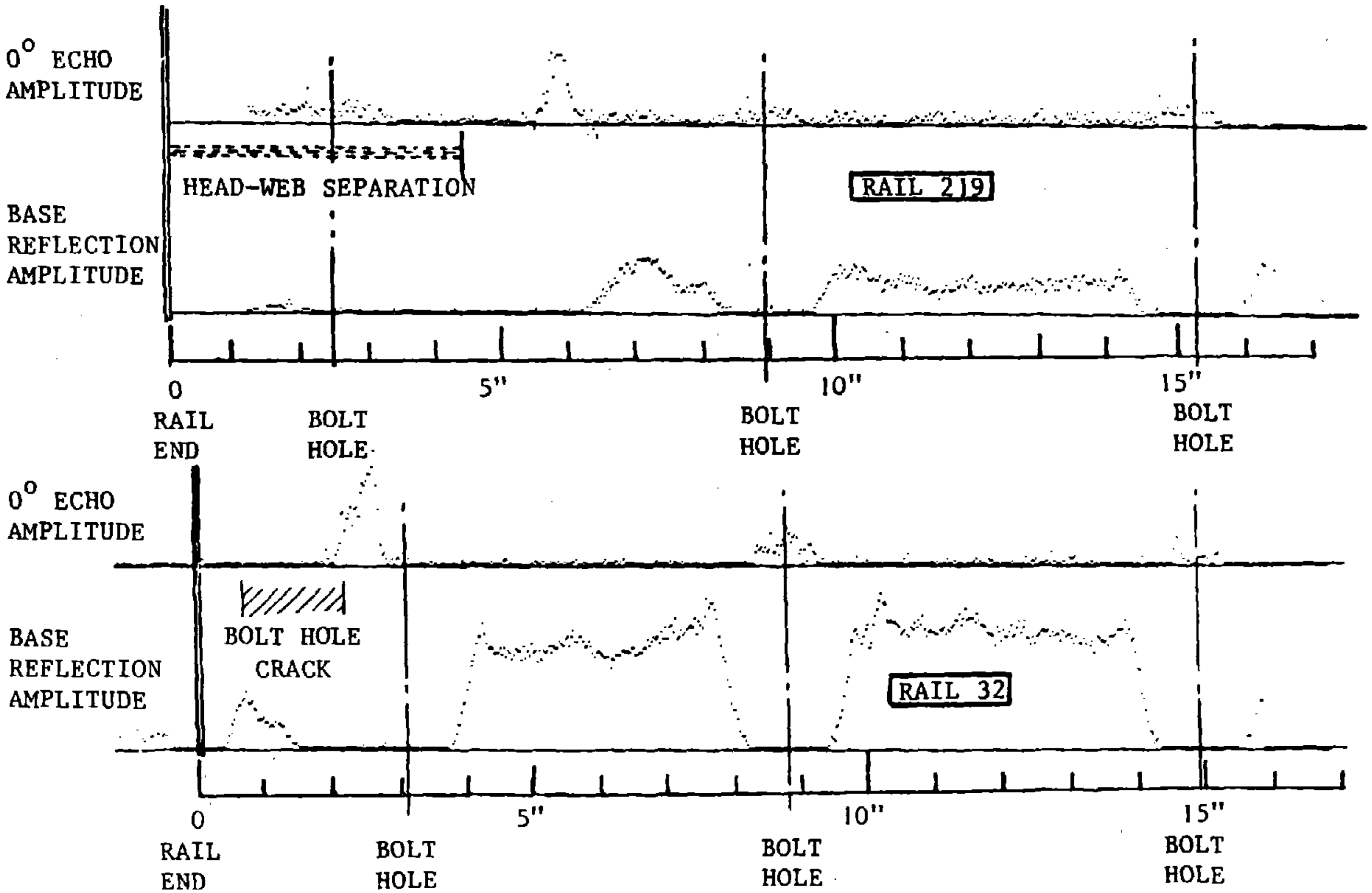


Figure 15. Computer generated graphs of the 0° EMAT base echo signal strength as a function of EMAT location over two rail samples with bolt holes and a head-web separation (top pair, rail 219) and a bolt hole crack (bottom pair, rail 32). These data were taken by moving the EMAT slowly along the rail with the system triggered by the time base clock.

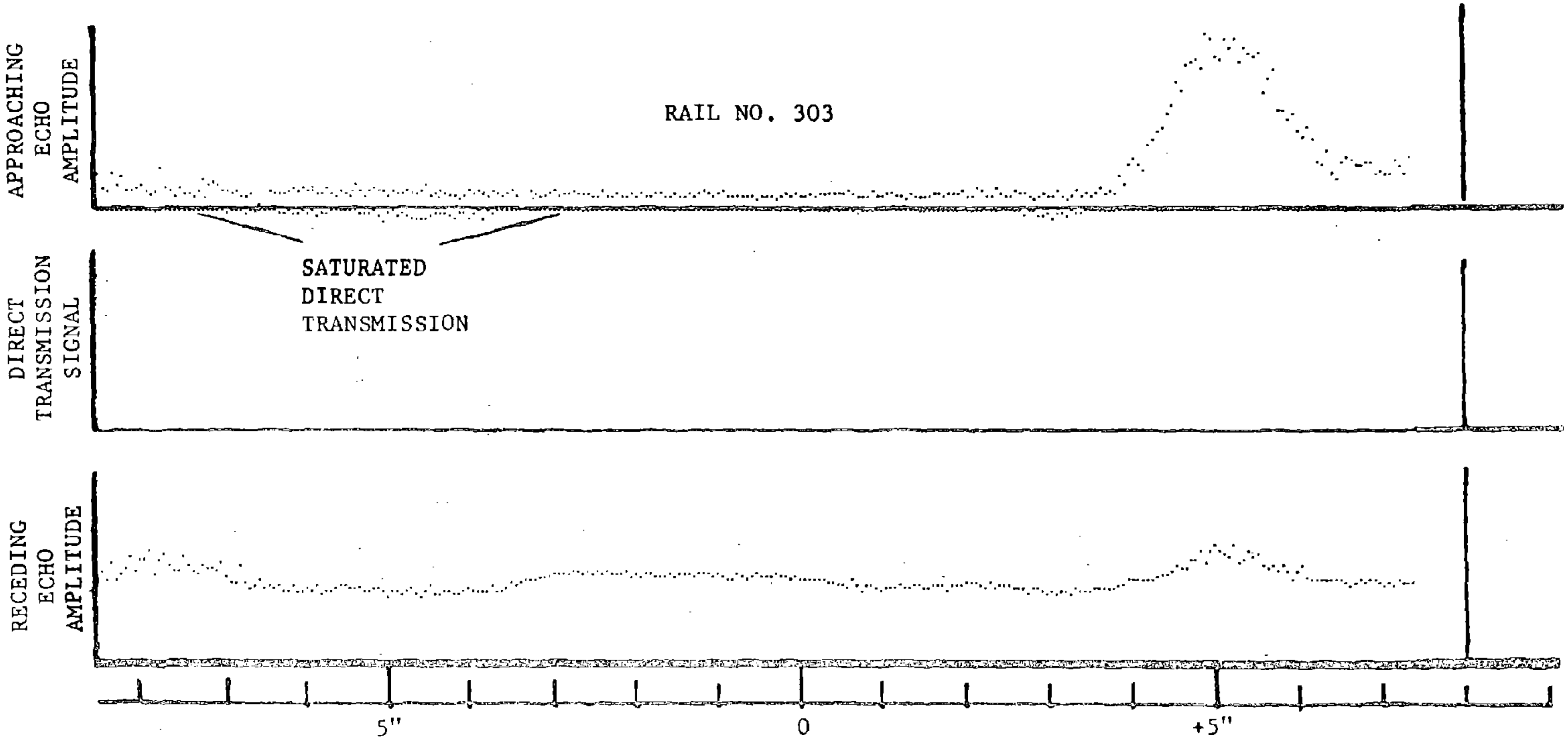


Figure 16. Detailed graphs of the 90° EMAT signal amplitude variations in the vicinity of a transverse defect in sample rail 303. These data were taken by moving the EMAT slowly along the rail with the system triggered by the time base clock.

causing a large echo in the receding echo channel so only a small maximum appears at the left hand edge of the receding echo graph. A small maximum in the receding channel at the same location as the maximum signal in the approaching channel is probably caused by an imperfect separation of the approaching and receding signals in the special filters at the output of the preamplifiers in the 90^{o} EMAT channel. This shows that the separation between the approaching and receding signal channels was actually only about -14 dB.

4.4.4 Electronic System Summary and Block Diagram

The paragraphs above describe the operation of the individual parts of the inspection system. Fig. 17 is a block diagram that shows the essential parts of the electronic system and allows the signal paths to be traced out. As depicted on the left hand side of the diagram, the inspection process is initiated by a trigger pulse from a clock for time-based measurements or from an odometer wheel for distance-based measurements. This trigger pulse enters a computer I/O Board to initialize the COMPAQ PORTABLE 286 computer which, in turn, proceeds to step through the timing diagram shown in Fig. 12. The Transmitter Drive Board (located in the Control Box on the towing vehicle) converts a trigger signal from the I/O Board into an RF tone burst suitable for driving the 90^{o} and 0^{o} transmitters that are located out on the EMAT carriages. The preamplifiers and phase shifting networks are also located on the EMAT carriages but their outputs are returned to the Control Box where the signals are filtered, windowed and channeled into the proper lines to be peak detected and stored on the sample-and-hold circuits. When the computer is ready, the I/O Board initiates the conversion of the voltages on the sample-and-hold boards into digital format and fills the buffer memory with the inspection data to be associated with a particular odometer count or clock pulse. When the buffer is full, its contents are assigned a file number and permanently stored on the hard disks of the computer. From there, the operator can command that the data be printed out, displayed on the CRT or processed for the strip chart recorder. A signal monitoring oscilloscope gives the operator the ability to monitor the size and shape of a wide variety of signals throughout the system for diagnostic purposes. Fig. 10

BLOCK DIAGRAM

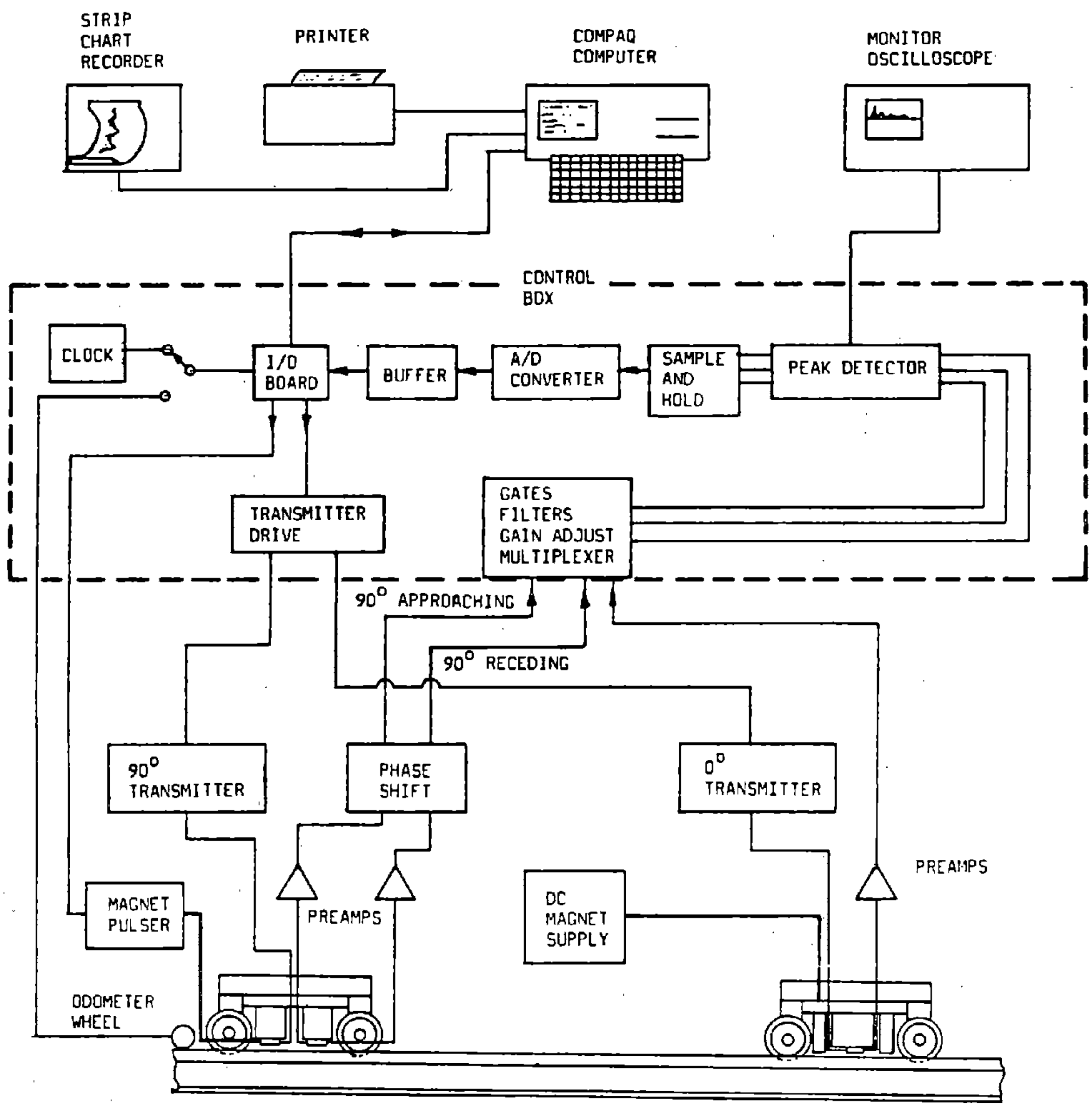


Figure 17. Block diagram of the inspection system for one rail.

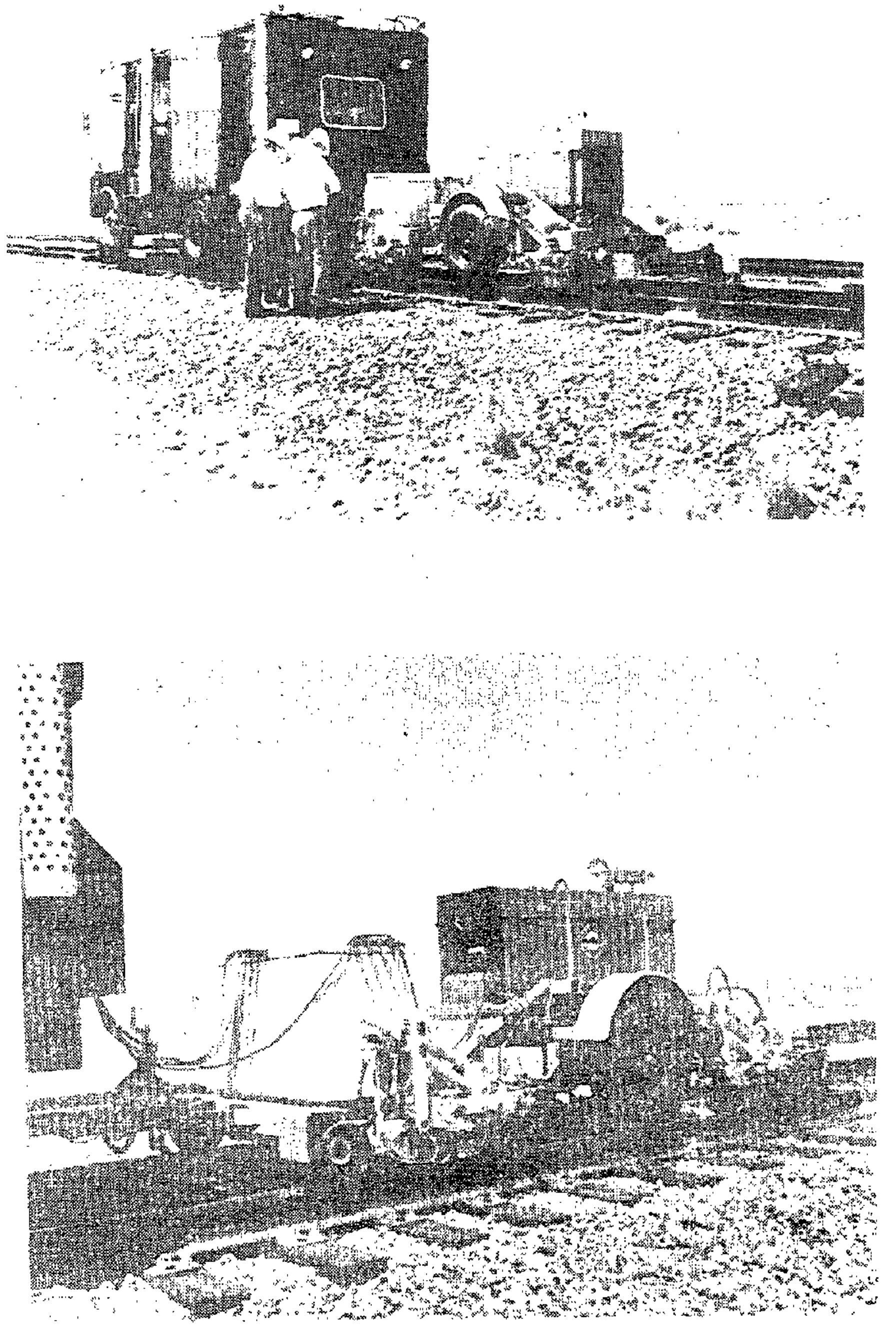


Figure 18. Photographs of the inspection trailer in place on the tracks at TTC in Pueblo, Colorado.

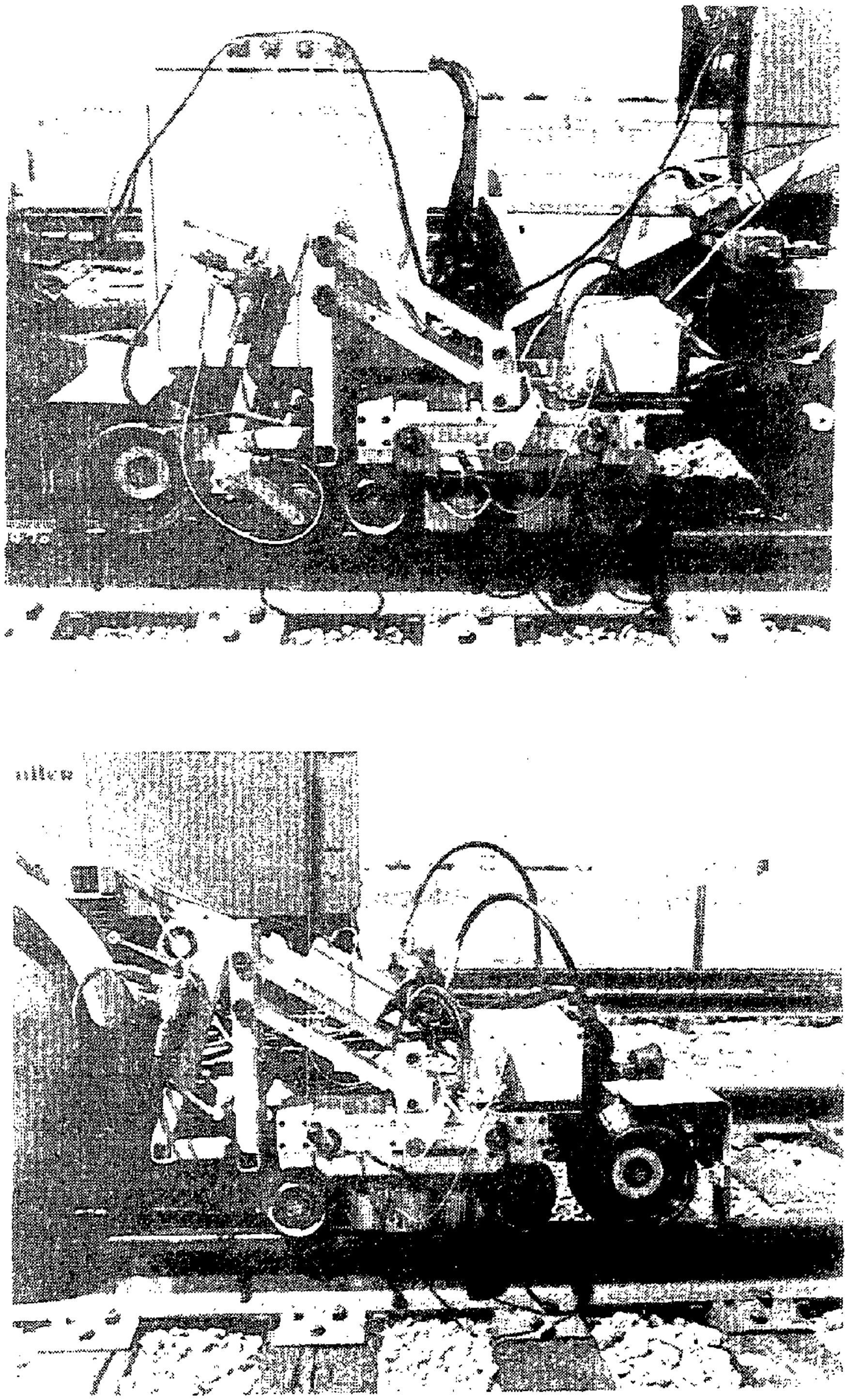


Figure 19. Photograph of the EMAT magnets and carriages. 90° EMAT (top) and 0° EMAT (bottom).

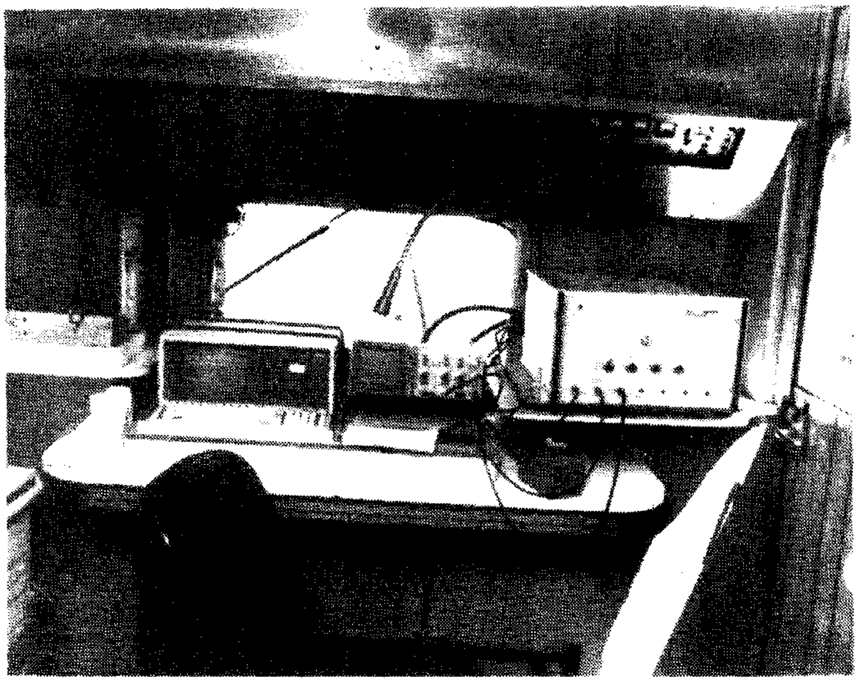


Figure 20. Photograph of the operator's station at the rear of the R-2 towing vehicle.

shows examples of several common signals. Appendix A gives operating instructions for the system and describes all these capabilities more fully.

5.0 OPERATION

5.1 DELIVERY TO THE TRANSPORTATION TEST CENTER

5.1.1 Inspection Configuration

After assembly of the trailer and the electronic instrumentation into a self-contained unit, the complete system was tested at Magnasonics on a row of sample rails which contained flaws that had been well characterized during the Rockwell International program. Only two EMATs were mounted on one side of the vehicle in order to test their performance before going to the expense of manufacturing and mounting copies on the other rail. Thus, all of the results presented in this report were obtained during inspection tests at low speeds and on only one rail. The data shown in Figs. 13, 14, 15 and 16 were obtained on the sample rails and gave assurance that the equipment was behaving as planned before it was sent into the field. A few short tests were conducted on tracks owned by the Atchison, Topeka and Santa Fe Railway in Albuquerque in order to verify the transportability and durability of the unit before it was delivered to TTC in Pueblo, Colorado during the last week of May, 1987.

Fig. 18 shows two photographs of the trailer on Section 10 of the Facility for Accelerated Service Testing (FAST) of the Transportation Test Center (TTC) as it was being readied for an inspection test. The towing vehicle shown was provided by the DOT specifically for this program and was called the R-2 Vehicle. Fig. 19 shows two close-up photographs of the EMAT carriages themselves. The 90^{o} EMAT was mounted in front, near the instrument container, while the 0^{o} EMAT was mounted near the rear wheel of the trailer.

Since the trailer was self-contained, the towing vehicle required no special outfitting except for a trailer hitch that was compatible with the trailer's towing fixture and some tiedown brackets to accept the control instruments that were moved from the instrument container on the trailer onto the towing car. Fig. 20 is a photograph of these control instruments in place on a shelf at the rear window of R-2. The two channel strip chart recorder (Gould Model 2107-2290-XX) can be seen next to the Compaq computer on the left while the signal monitoring oscilloscope (Tektronix Model 2213A) is at the right of the computer. On the far right, the system Central Control Unit sits on a shelf by itself. The small box in front of the Control unit is an emergency ON-OFF switch. The view of the printer for the computer is cut off by the left edge of the photograph.

5.1.2 Start-up Procedure

Detailed instructions on how to activate the system are given in Appendix A. When followed, the signal monitor oscilloscope should display a base echo on the 0^o channel and a direct transmission signal on the 90^o channel both of which should be at 8 volts in amplitude. The pens of the strip chart recorder should be at midscale and deviate from this line only if the above signals fall below 5 volts or a flaw echo that exceeds the threshold is detected.

5.1.3 Calibration or Sensitivity Selection

Section 10 of the TTC FAST track contains several well documented, natural defects plus machined holes of various diameters and depths. In order to establish a basic sensitivity for an inspection run, it is useful to set the system variables such that a geometrically well defined ultrasonic target yields an easily recognized output or display. For this purpose, a row of 1/4" and other diameter holes drilled into the side of the head of the rail in Section 10 was scanned with the inspection trailer and the gain in the 90^o channel was set to yield a large deflection on the strip chart recorder when the sound beam passed over the deepest hole. Forcing the strip chart to give a large deflection for a small flaw is of great importance to the operator because it tells him that the system has located an unusual group of signals and where to look in the computer memory to get detailed information on the region. Such a deflection can be achieved in spite of the settings established in the set-up procedure by increasing the gain far beyond the point where the direct transmission signal saturates the amplifiers and produces a signal that stays at a constant 10 volt level. Under these conditions, the computer normalizes the small flaw signal by dividing it by the constant 10 volts, multiplies the quotient by 250, checks to see that the result exceeds the threshold and deflects the recorder pen accordingly. Fig. 21 shows two different strip chart recordings obtained when the inspection vehicle was scanned over the 1/4 inch diameter holes drilled into the side of the head of a rail. Only the strip charts for the 90^{o} EMAT channel are shown and the gain has been increased until the hole that was drilled completely through the head caused a near full scale pen deflection in both the approaching and the receding channels. At this same gain setting, the hole drilled only halfway through the rail deflected the pen only when the system approached the hole. This is probably because there was an unbalance in the phase sensing circuits that separate the approaching and receding signals.

6.0 RESULTS

6.1 INSPECTION OF TTC RAIL

With the system gains adjusted as described above and while the system sat on the rail containing the side drilled holes, an inspection scan was begun near tie 467 where a transverse defect was known to exist. Fig. 22 shows the strip chart output from this scan. Channel 2 of the recording shows the output of the 90^{o} EMAT which displays a midscale pen deflection in the absence of defect indications. The transverse defect at tie 467 (at the start of the scan in the upper left) appears as two up-scale deflections at the very beginning of the trace immediately followed by very large deflections that are characteristic of a rail joint. Joints between rails show an increased pen deflection as the echo from the rail end approaches, followed by the complete disappearance of the signal while the gap between rails passes between the transmitter and the receiver and then the second large pen deflection as the rail end puts an echo into the receding channel. Note that this "M" shaped signature occurs at regular intervals in the chart record as the inspection vehicle passes over the rail ends at regular distances. Immediately following the rail joint at tie 463, the rail head between ties 463 and 441 appears to be covered with ultrasonic reflectors because the pen is frequently moved up

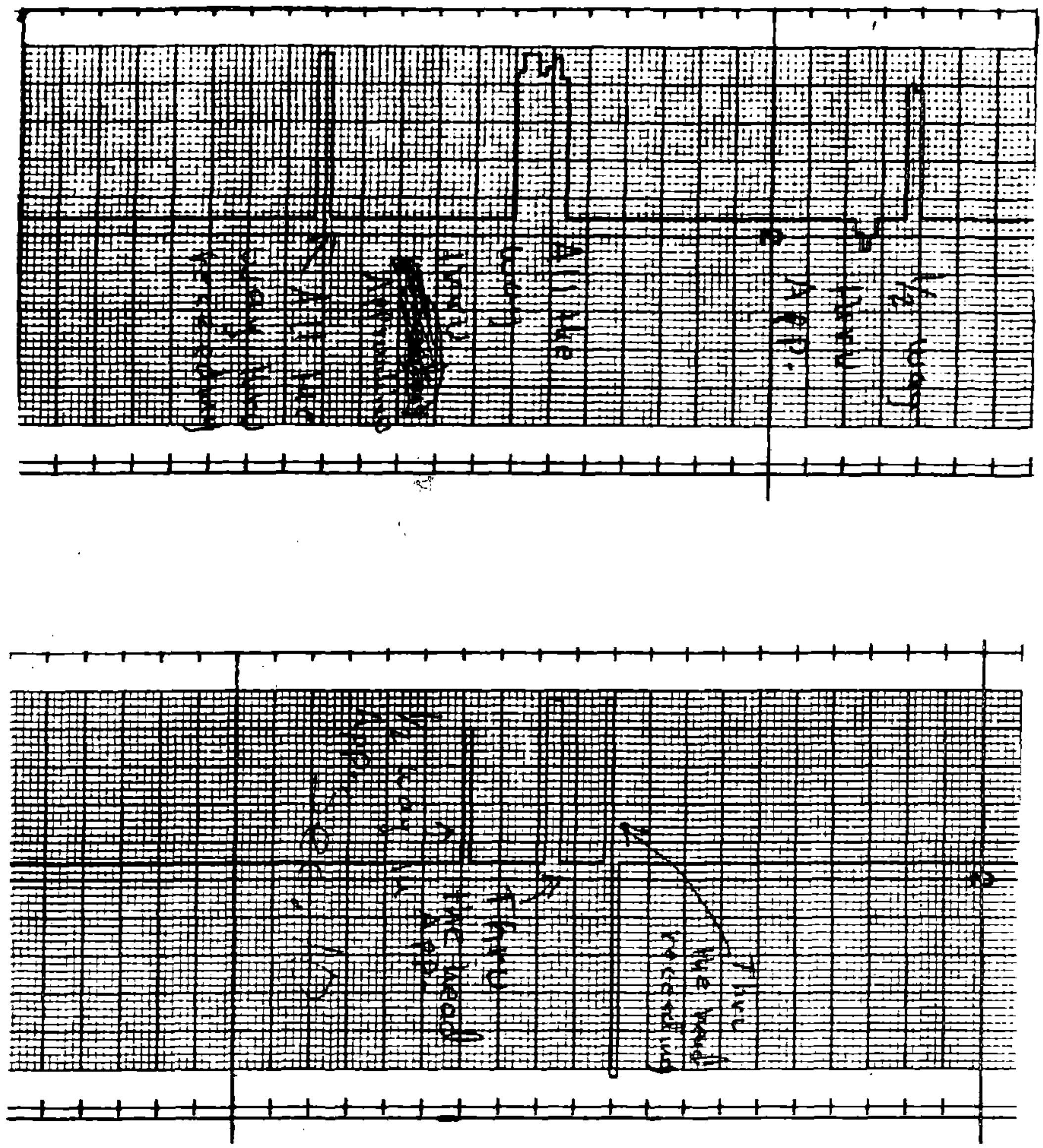


Figure 21. Two separate strip chart records showing the passage of the 90° EMAT over 1/4 inch diameter holes drilled into the side of the rail head. Only those holes that extended halfway or all the way through the head were detected.

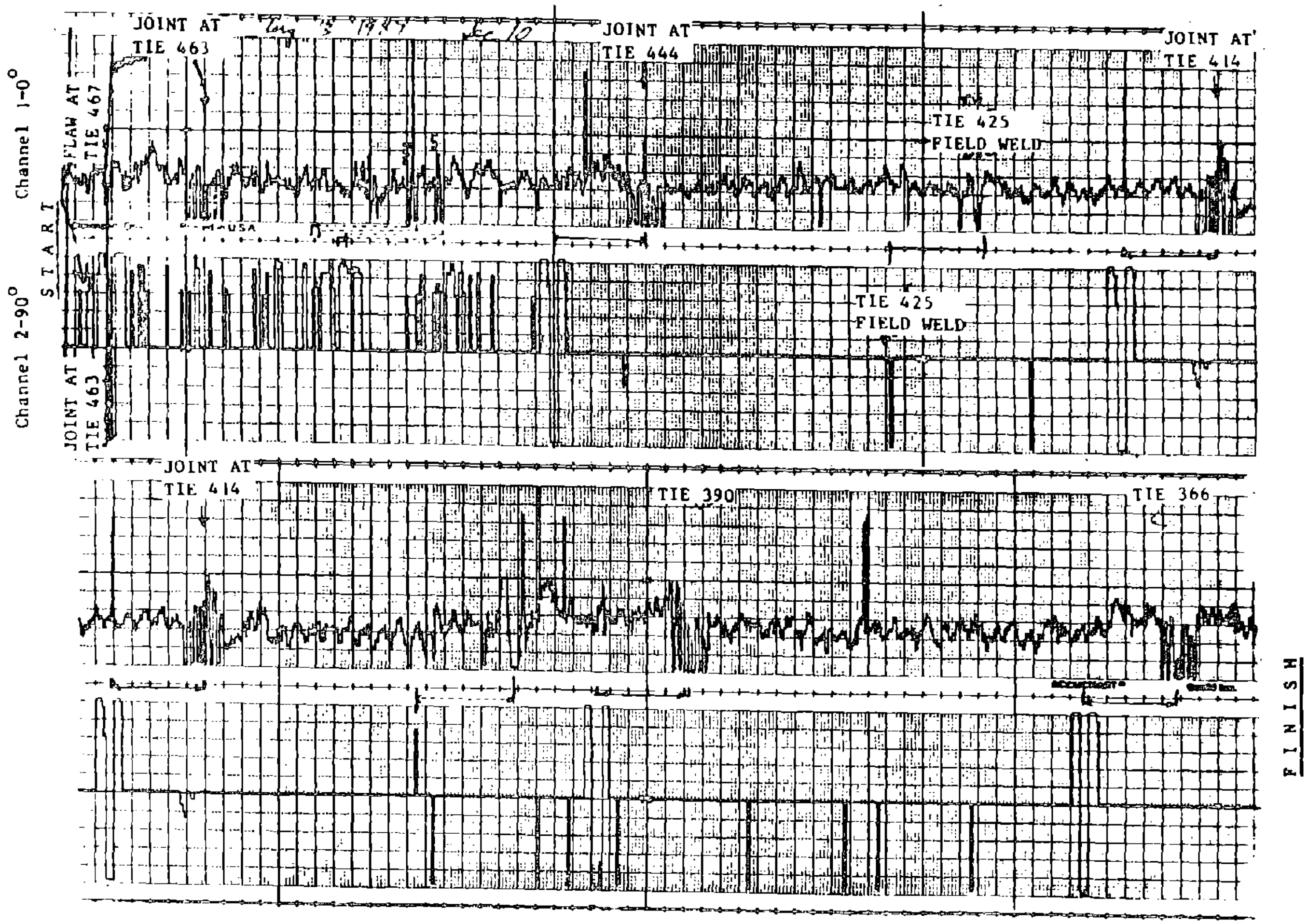


Figure 22. Example of test results obtained on Section 10 at TTC from Tie No. 467 to Tie No. 383.

scale as the scan continues. Following tie 441, the other rails in the scan shown on Fig. 22 are free of these indications. A visual examination of the rail between ties 463 and 441 showed that it was badly shelled so it was presumed that some of the surface cracks actually curved deeper into the surface and penetrated far enough to cause reflections of the SH waves. Metallographic examination of this rail will be needed to verify this interpretation. Only one other indication of a flaw in the rail head appears in Fig. 22 and that is between ties 414 and 390 at about tie 399 where only one approaching or receding channel records an echo. More careful examination of this signal should be performed by examination of the computer records or by visual inspection. Fig. 22 also shows a few downward deflections of the recorder pen which were not correlated with any unusual signals in the 0^{o} EMAT channel or any visible property of the rail. Further investigation is needed here.

Channel 1 or the top trace in Fig. 22 displays the output signal of the 0^{o} EMAT. Here the channel gain was insufficient to saturate the base echo and keep the pen at midscale so the chart records all the small variations in EMAT efficiency as a function of position along the track. Although these pen fluctuations are distracting and could have been suppressed by simply increasing the 0^{o} EMAT gain, the disappearance of the base echo at the bolt holes near each joint is clearly resolved and provides another characteristic signature that can be used to recognize a joint. Note that the joint features in the 90^{o} and 0^{o} channels are uniformly displaced from one another by about five large chart divisions because the 0^{o} EMAT follows behind the 90^{o} EMAT by 89 inches and, hence, passes over the same feature in the rail at a later time. Under conditions of common practice, the gain in the amplifiers would be kept high enough to saturate the signal and keep the pen steady at midscale so that the bolt holes and joints would stand out on the chart presentation and any other disruptions of the ultrasonic signal through the web would also be easily detected. One such disruption would be at field welds where the weld bead or flash distorts the base of the rail and eliminates a clear echo from the base. One such dip in the base reflectivity was indeed identified as a field weld at tie 425. Another, similar dip in signal at tie 399 may also be a weld and may have caused the echo that appears in the 0^{0} EMAT inspection channel that was discussed above. Other prominent zeros in the base reflectivity occur near ties 453 and 451 and accompany the shelling in that particular rail. There are several very short duration up-scale deflections on the 0^{o} channel that would indicate very short and strong reflectors in the web or head. Since no such flaws were known, these pen excursions were considered to be some sort of random noise and were ignored unless they persisted for a long distance.

Appendix B collects together both the computer printouts and the associated strip chart records for a variety of well known defects in Section 10. They have been grouped according to the channel in which the unusual signal features were prominent in order to compile a catalog of characteristic signatures for each type of flaw according to the EMAT that is most seriously effected. Pages B-1 through B-3 describe three transverse defects in the head. The flaw shown on Page B-1 was not anticipated by the TTC staff but gave a clear indication both to the computer and to the strip chart. The transverse defect (TD) at tie 463, shown on Page B-2, appears to be very close to the rail end and exhibits a large echo in the receding channel. Pages B-4 through B-8 describe flaws detected with the 0^{o} EMAT. Pages B-4 and B-5 show how the computer printouts and the strip charts respond to field welds and small holes in the web, respectively. Pages B-6 and 7 show how bolt hole cracks cause the regular shape of the "shadow" cast by a bolt hole to be distorted and expanded by the presence of a crack at one hole. The small head/web separation shown on Page B-8 appears primarily in the echo channel of the computer printout. In all of these examples using the 0^{o} EMAT, there appears to be excessive electronic noise in the echo window and is plotted out by the computer as individual points. (The fact that the individual points are in vertical pairs is an aberration introduced by the printer.)

6.2 RESULTS OF THE EVALUATION TESTS

For two months after delivery of the system to TTC and following the training of the TTC staff, the system was evaluated by operators skilled in Nondestructive Testing with only repair support by Magnasonics personnel. Following this two month trial, two major criticisms were reported. The first was that some known transverse defects in the head of some rails were not detected. It was determined that the most probable reason for missing these reflectors in the head was because the transducers had lost their sensitivity in the particular rails containing the flaws. Such a determination was possible because the system naturally monitored the transduction efficiency of the 90° channel by continuously recording the amplitude of the direct transmission signal. As pointed out by Rockwell International, verified by Magnasonics at the start of the program and shown in the histograms in Figs. 3 and 6 of this report, it was to be expected that a few rails would be found that had weak magnetostrictive coefficients and hence would require some special adjustments to the gain of the 90° EMAT channel.

The second criticism was that the strip chart records often appeared to be very "noisy" and it was difficult to distinguish up or down deflections caused by flaws from deviations of the pen position from the middle of the chart caused by local fluctuations in the strength of both the base echo in the 0° channel and the direct transmission signals in the 90° channel. This second criticism could also be traced to variations in the transducer efficiency but such a conclusion was unexpected because the 0° EMAT does not rely on a magnetostrictive coefficient for its sensitivity.

Figure 23 shows an example of these criticisms taken from experiments performed by Magnasonics in August, 1987, after the evaluation tests in order to clarify the nature of the problem. For these experiments, the strip chart recorder was set up to display the 0° base reflection amplitude and the 90° direct transmission signals as measures of the local transduction efficiency. A rail with excellent signals was chosen to define the full scale deflection so that poor efficiency could be measured quantitatively by how far below full scale the pen remained on other rails. The figure shows that between ties 685 and 667 (a distance of about 30 feet) there was low efficiency in the 0° EMAT and high efficiency in the 90° EMAT. However, a few rail lengths away, the 90° EMAT was exhibiting low efficiency over a comparable distance (between ties 630 and 606) while the 0° channel had

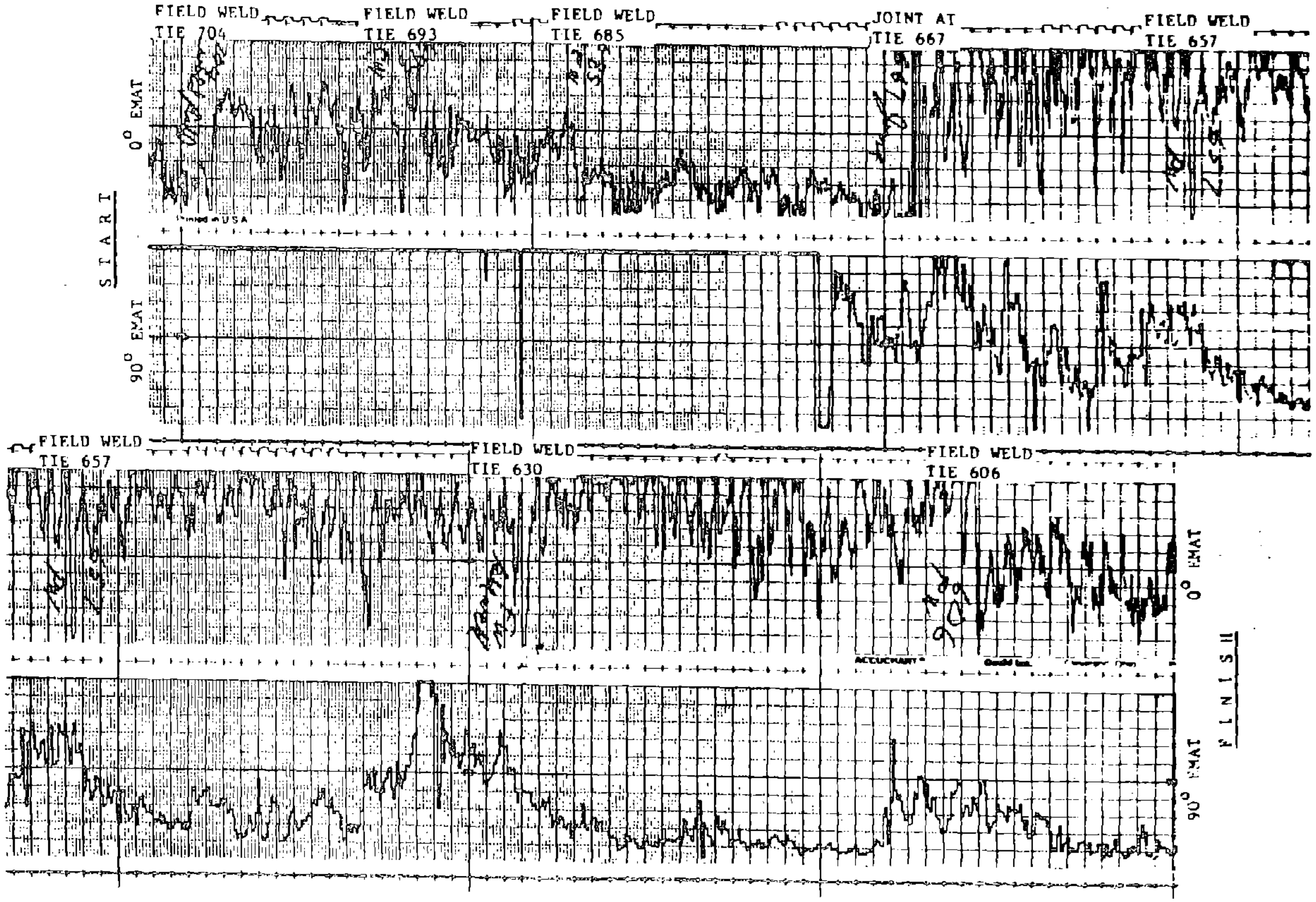


Figure 23. Examples of low efficiency rail inspection (Section 10, Ties 704 through 600).

acceptable efficiency. By collecting data similar to that shown in Fig. 23 over all of Section 10 at FAST, it was possible to construct a graph to show the statistical distribution of low efficiency rails in that section. This graph is presented in Fig. 24 which displays the percentage of rails that exhibited an efficiency lowered by the amount indicated on the abscissa of the graph. Note that all of the rails are represented in the data obtained with the 0° EMAT but that 30 percent of the rails tested with the 90° EMAT showed higher efficiency than the reference level chosen for this data set. It is clear that the distribution of efficiencies is very broad for both EMAT types and that about 10 percent of the rails have signals that are 20 dB (a factor of 10) lower than a comfortable level. This is not so serious for the 0° inspection because the flaw information is contained in a signal drop of more than 20 dB around bolt holes and split webs or heads. For the 90° EMAT inspection, these measurements mean that the 90° channel gain must be increased by about 20 dB to be sure that small transverse defects are not missed in rails of low efficiency.

6.3 RECOMMENDATIONS

1. Although more than 80 percent of the rail length investigated at TCC showed good to excellent transduction efficiencies, inspection of the remaining 20 percent will require an improvement of the overall signal-to-noise ratio by 10 to 20 dB. This level of signal improvement can be achieved without increasing the noise by introducing the following improvements:

   a. Increase the transmitter power of both the 0° and 90° EMATs by replacing the old transmitter circuits with more powerful units that have recently become available commercially.

   b. Replace the 0° EMAT DC electromagnet with a unit having a larger iron core and hence is capable of delivering more magnetic flux. Modify the 0° EMAT coil design to use this higher flux more efficiently.

   c. Install more efficient 90° EMATs that excite and detect SH waves by the Lorentz force mechanism and thus avoid the loss of

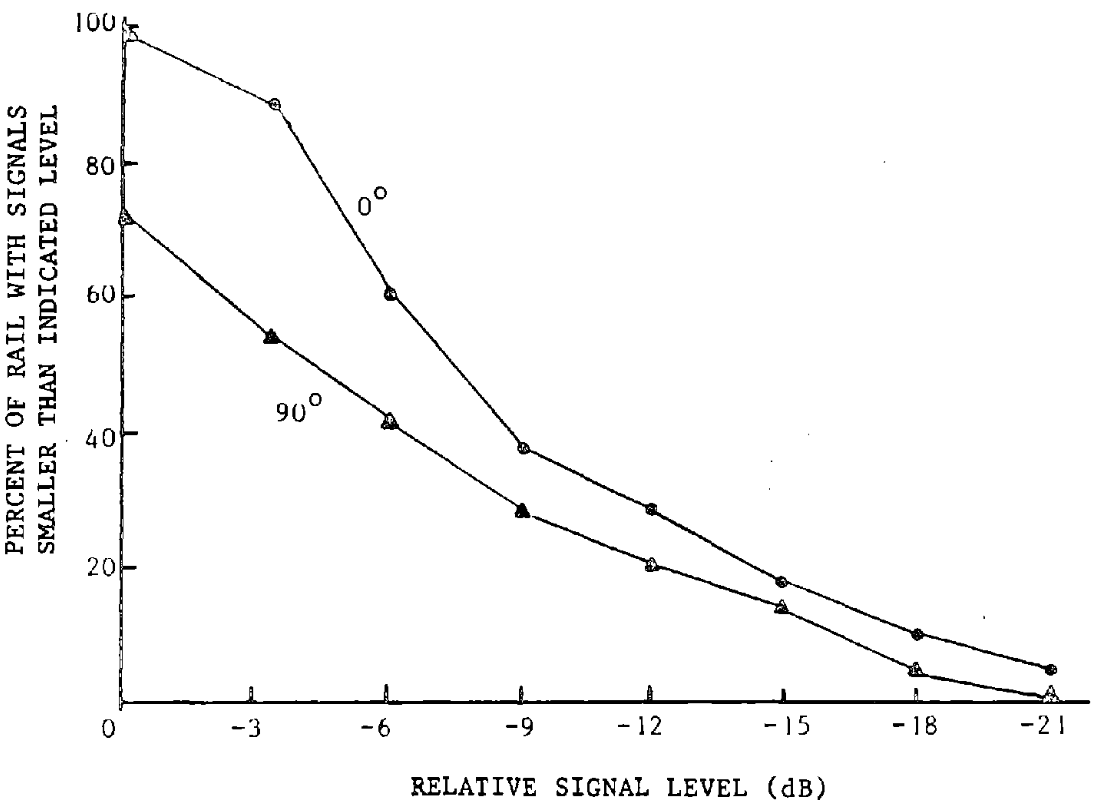


Figure 24. Statistical distribution of EMAT efficiencies along all of Section 10 of the FAST tracks.

efficiency caused by low magnetostrictive coefficients in a small percentage of rails. Such EMATs are currently under development on other programs at Magnasonics.

2. The appearance of the strip chart recorder output should be made easier to interpret by suppressing the fluctuations introduced by local EMAT efficiency variations. This can be accomplished by:

a. Using the gain increases recommended above to keep the base echo and direct transmission signals well above saturation so that the chart pens will stay at the center of the chart.

b. Add logarithmic amplifiers to the input of the strip chart recorder so that the logarithm of the signal level will be plotted on the chart instead of the signal itself. This will make the chart read out in dB.

c. Actively reduce the gain during the time that the Direct Transmission signal is under the 90° EMAT receiver. This will allow the highest possible gain to be used when flaw echoes are expected and make the normalization procedure more effective.

3. After the circuit modifications listed above have been incorporated and their improvements in performance have been established, the following additions to the system should be incorporated in order to make it more acceptable for testing on commercial railroads.

a. Add the improved EMATs and circuits to the second rail. The mechanical hardware and the data processing software are already available for this extension of capabilities.

b. Develop experience and then software to make off-line analysis of the data stored in the computer memory a practical tool for rail inspection by NDT trained personnel.

7.0 SUMMARY AND CONCLUSIONS

This report describes the results of a two-year program to demonstrate the advantages of using couplant-free, electromagnetic transducers for rail inspection on a vehicle that could be operated on revenue producing railroad tracks by personnel trained in Nondestructive Testing. The final product was evaluated by the NDT staff of the Transportation Test Center at Pueblo, Colorado, who found that it operated well on 80 percent of the rails in their tracks. To adequately inspect the remaining 20 percent of the rails will require some improvement in transducer efficiency and data processing procedures. Operation on the high efficiency rails demonstrated the following advantages of using electromagnetic transducers (EMATs) combined with computer control of the inspection process.

1. The utilization of EMATs permits:

a. Operation on lubricated or dirty rails without any special preparation of the rail head surface and the elimination of a need to carry a large supply of special couplant fluids.

b. Use of special shear waves that can give a more thorough inspection of the rail head for transverse defects and the rail web for vertical split head type flaws.

c. Capabilities for much faster inspection speeds.

d. Continuous monitoring of the quality of the signals in the rails and the normalization of the data to make the inspection results nearly independent of the coupling efficiency.

2. The incorporation of a simple personal computer permits:

a. Permanent, mass storage of the essential features of the ultrasonic signals at each point along the rail.

b. Real time processing of the signals to present the operator with a more informative and easily interpreted display.

c. Reanalysis of the raw data at different threshold levels to expose and give detailed analysis to borderline cases in an off-line environment.

d. The potential for the development of pattern recognition techniques that will ultimately allow the computer to make accept/reject decisions.

3. The inspection vehicle itself is a self-contained trailer that can be towed by any high-rail car along the highway or on the railroad tracks. It therefore permits:

a. Each EMAT sensor to be supported by its own hydraulically operated carriage that can pass through frogs and switches without harm.

b. The position of each sensor relative to the gage face of the rail head to be adjusted by a hand crank.

c. Both dc and ac power to be supplied by a motor/generator on the trailer.

d. Portable display and control instruments to be placed inside the towing vehicle and connected to the trailer through an umbilical cord.

8.0 REFERENCES

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2. "Ultrasonic Inspection of Rails by Electromagnetic Transducers (EMATs), Contract DTFR53-80-C-00121.
3. L. J. Graham and J. F. Martin, "Ultrasonic Inspection of Railroad Rails by Electromagnetic Transducers (EMATs)," Final Report No. FRA/ORD-86-09, May 1986.
4. E. R. Dobbs, "Electromagnetic Generation of Ultrasound," Research Techniques in Nondestructive Testing, Vol. 2, 1973, pp. 419-441.
5. G. A. Alers and L. R. Burns, "EMAT Designs for Special Applications," Materials Evaluation, Vol. 45, pp. 1184-1189, October 1987.
6. B. W. Maxfield, A. Kuramoto and J. K. Hubert, "Evaluating EMAT Designs for Selected Applications," Materials Evaluation, Vol. 45, pp. 1166-1183, October 1987.
7. C. F. Vasile and R. B. Thompson, "Periodic Magnet, Noncontact EMAT—Theory and Application," Proc. IEEE Ultrasonic Symposium, 1977, IEEE Catalog No. 77CH1264-ISU.
8. W. E. Peterson and R. B. Thompson, "Electromagnetic Acoustic Transducer," U. S. Patent 4,434,663, March 6, 1984.
9. R. Bruce Thompson, "New Configurations for the Electromagnetic Generation of SH Waves in Ferromagnetic Materials," Proc. IEEE Ultrasonic Symposium, 1978 IEEE Catalog No. 78CH-1344-ISU.

APPENDIX A

Instruction Manual

APPENDIX A

EMAT RAIL FLAW DETECTION SYSTEM

INSTRUCTION MANUAL

I. TURN ON PROCEDURE

A. Check to see that the welder emergency kill switch (RED) is pulled out, the DC magnet switch (YELLOW) is pushed down and the AC magnet switch on the Control Box is up. The computer, printer, oscilloscope, strip chart recorder and Magnasonics power supply (in electronic cabinet on trailer) should be OFF.

B. Lower the carriages onto the rail by pushing the yellow levers down (ON) and pushing the directional valves to the down position. Make sure the wheels are seated on the rail.

C. The transducers should be centered on the head of the rail by adjusting the hand crank on each carriage.

D. Turn the welder on by switching the ignition switch to the RUN position and depressing the start switch. In cold weather the choke may need to be pulled out.

E. Turn on any power supplies in the instrument cabinet and then the other instruments and the computer in the towing vehicle.

F. The computer will spend some time configuring itself and then display C:/rail. Press RETURN after each command.

G. Type in PRTSCRN to activate the printer for graphics.

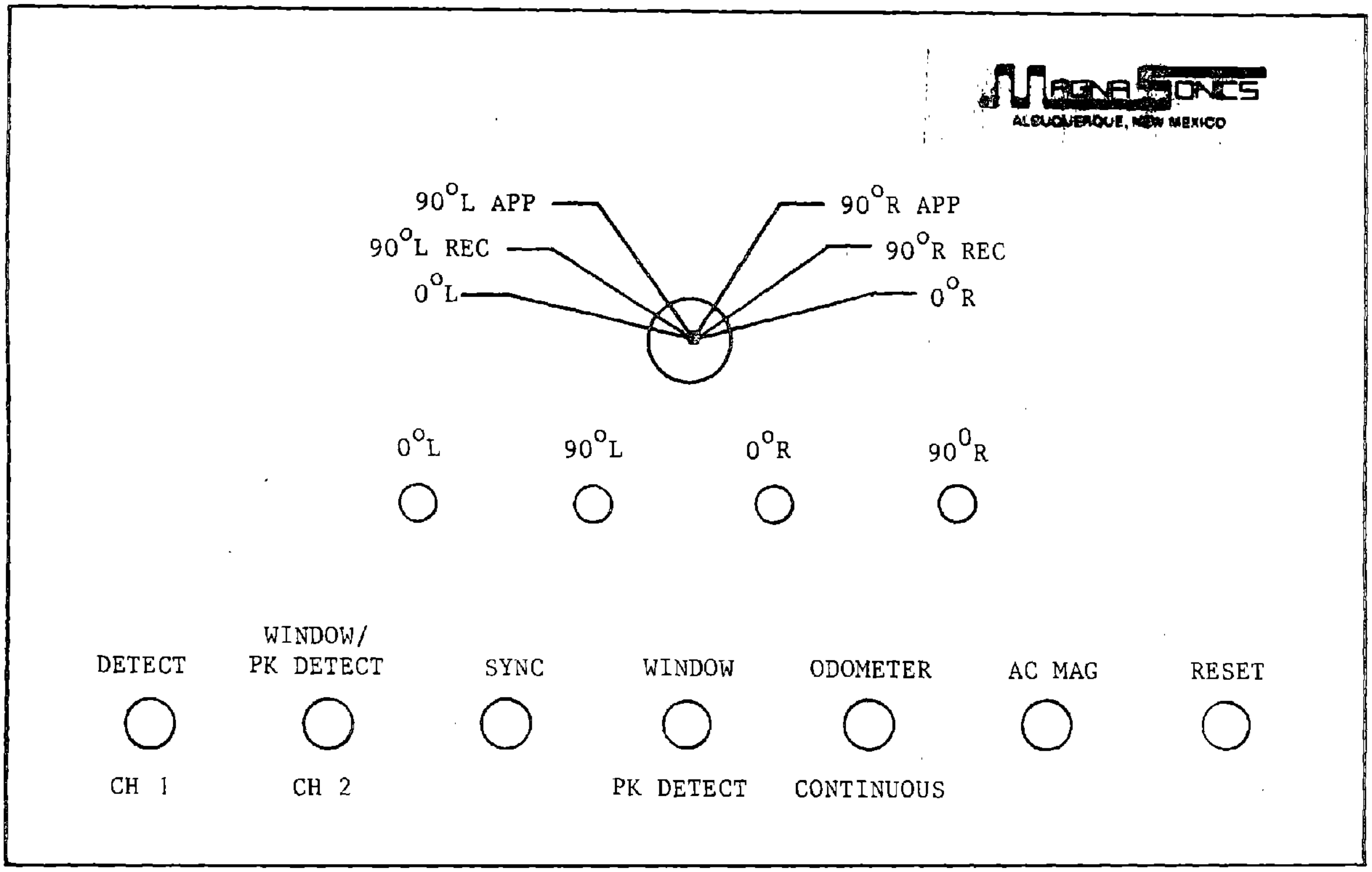
H. The computer will display a second C:/rail.

I. Type in RAIL. The program will load and display the main menu.

J. Set the Monitor Oscilloscope controls on 1 volt/div. and 20 μs/div. DC coupled. Set the sweep controls to Normal, Ext. Trig., no delay.

II. FLAW INSPECTION SETUP PROCEDURE

A. After completing the Turn On Procedure listed above, switch the front panel toggle switches on the Control Box to WINDOW and to CONTINUOUS position. AC magnet switch should now be toggled down. A drawing of the front panel of



SIX POSITION ROTARY SWITCH - switches the different ultrasonic signals to Channel 1 of the oscilloscope.

- 0°, 90° - ultrasonic beam angle (relative to vertical)
- L, R - left or right hand rail
- APP - approaching
- REC - receding

10 TURN POTENTIOMETERS - control of the gain in each ultrasonic channel.

BNC CONNECTORS - connection points for signal monitoring oscilloscope.

DETECT - CH 1: connection point for Channel 1 of the oscilloscope. Displays the detected ultrasonic signal.

WINDOW/PK DETECT - CH 2: connection point for Channel 2 of the oscilloscope. Displays either the window signal or the voltage level output of the largest signal within the window.

SYNC: connection point for sweep trigger of the oscilloscope.

TWO POSITION SWITCHES - sets routing of various signals within the system.

WINDOW - PK DETECT: selects the signal to be displayed on Channel 2 of the oscilloscope.

ODOMETER - CONTINUOUS: selects either the odometer or the internal clock for triggering the entire system.

AC MAG: On/Off switch for the pulsed magnets.

RESET: Resets the computer to the beginning.

Figure A-1. CONTROL UNIT - EMAT Rail Inspection System the Control Box is shown in Figure A-1 along with an explanation of the function of each control.

B. Type 5 into the computer to select RUN THE SYSTEM. The computer displays for each menu selection are shown in Figs. B-1, B-2, B-3 and B-4.

C. Check the 0^{o} signal by switching the monitor selector rotary switch to 0^{o}L (See Figure A-1). The 0^{o} signal should be displayed along with the gates (windows) for 0^{o} signals.

D. On a good rail section, set the gain knob (0^{o}L) to get a full screen base reflection.

E. Check the 90^{o} signal by switching the monitor selector switch to 90^{o}L REC to monitor the 90^{o} Direct Transmission.

F. Adjust the gain knob 90^{o}L to get a full screen Direct Transmission.

G. The computer display should display both the 90^{o} Direct Transmission and 0^{o} base reflection as a line going across the screen. If the DT for 90^{o} is not being displayed on the fourth slot of the computer screen, reset the switch on the front panel until the trace appears on the computer screen.

H. Turn the strip chart recorder on and place its controls in the 5 mm/second ÷ 100 mode. Check to be sure that the pens are in the center of the paper.

I. If the pens are sitting at full scale deflection, the program must be reinitialized by pressing the return key three times and then reentering the program by typing in RAIL and, when the menu comes up, typing in 5 to Run the System.

J. Inspection of the rail can now be done either based on an internal clock (continuous mode) or based on the odometer (odometer mode). During the odometer mode, the inspection vehicle must be in motion in order to generate the trigger pulses that allow the computer to process the data.

NOTE: Before leaving the RUN mode, be sure that data you want to save has been copied on a floppy disk. Otherwise, the system will overwrite on the previous data files. To remind you of this danger, the computer will show FILE ALREADY EXISTING and you must RESET system and go to Menu 4 and observe signals on monitor scope before proceeding.

III. SETTING THE FILE NUMBER

A. The computer memory is subdivided into files that contain the detailed ultrasonic signal amplitudes for the 0° and 90° EMATs on each section of rail.

B. The marker pens on the far left and right edges of the strip chart are programmed to indicate the file number associated with each section of the chart. The number of deflections on the left hand pen shows the least significant bit of the file number while the right hand deflections show the most significant bit. (Example: File number 47 will contain the detailed ultrasonic data for the strip chart record that shows seven pulses on the left edge of the chart and four pulses along the right edge.

IV. TO SET WINDOWS

A. Select No. 3 from the Main Menu. The units to be used are microseconds.

B. Items 1 and 2 set the Delay and Width, respectively, of the 0° windows. Usually only two windows are used; the first brackets the echoes from the head and web that precede the base echo. The second window brackets are the base echo.

C. Items 3 and 4 set the Delay and Width, respectively, of the 90° windows. The first brackets, the Direct Transmission and the second brackets echoes that follow the Direct Transmission.

V. TO SET THE THRESHOLDS

A. Select 3 from the main menu. The following will be displayed on the screen:

Input DT flag

Input threshold 1 through 9

Always keep DT flag = Ø.

B. Only thresholds 1, 3, 5 and 6 are used in the single rail inspection system.

C. Threshold 1 sets the threshold for 0 degree reflections that arrive in the window preceding the base echo. A threshold setting of 1 corresponds to ≈ 40 mV (a setting of 255 = 10V or full scale). If this threshold is exceeded for two firings in a row, the strip chart recorder will switch from displaying the base reflection to displaying the web reflection amplitude. There is no threshold setting for the base echo.

D. Threshold 3 sets a 90 degree Direct Transmission default value. If the DT falls below the threshold 3 value, the threshold value and not the actual value is used to normalize the flaw reflection data. In this way, the computer will not have to divide by a number close to zero. Again, a setting of 1 = 40 mV and 10 = 0.4 volts.

E. Threshold 5 sets a threshold for activating a strip chart recorder pen to register the normalized 90^{o} receding flaw signals. If the flaw threshold is exceeded, the strip chart recorder will switch from displaying the Direct Transmission value to showing the normalized flaw value in volts, upscale from the normal pen position. Normalization means that the flaw reflection value is divided by the DT (or the DT threshold value if the DT is smaller than the threshold). Since the ratio will normally be small, it is multiplied by 250 and then compared to the flaw threshold value. Thus, the strip chart deflection D = 250 x Flaw Signal/DT Signal amplitude were 0.8 volts and the DT was 8 volts, then the normalized flaw value would be 1/10. The value to be compared with the flaw threshold will be 25 times 40 millivolts per unit or 1 volt.

F. Threshold 6 sets the threshold for the 90^{o} approaching flaw signal and uses the same logic as in E.

G. Once the values have been selected, hit RETURN and go back to the main menu.

V. <u>TO DISPLAY DATA THAT HAS BEEN STORED ON THE HARD DISK</u>

A. Select 6 on the rail program menu.

B. Input file number to be displayed. The first set of data will be displayed. To advance to the next set of data, type any key. There are 5 sets of data for each file.

While recording data, the file number is recorded on the strip chart recorder marker pens. The left pen indicates the 1's and right pen the 10's. Three pulses on the left pen and 2 on the right pen would be 23. Three digits must be entered to select the data file number. File No. 1 is 001, etc. To return to the main menu, type "M" <u>while</u> the data is being displayed.

VI. <u>TO COPY DATA ONTO FLOPPY DISKS</u>

A. Place formatted data disk in drive A.

B. Type in COPY RAIL001.RAW A: for file No. 1 to be copied. (Type 002.RAW A: for file No. 2, etc.).

C. Type in COPY RAIL???.RAW A: and the computer will store the first 14 files.

D. Type in COPY RAIL02?.RAW A: and the computer will store files 20 through 29.

VII. <u>TO DISPLAY THE DETECTED SIGNAL OUTPUT</u>

A. This operation does not need the computer except to choose the window as described in IV.

B. Place the switch on the front of the Control Unit (Figure A-1) down toward PK DETECT and Channel 2 of the oscilloscope should show a horizontal line whose voltage level measures the peak amplitude of the detected, ultrasonic signal in the window.

APPENDIX B

Rail Flaw Detection CRT Display Menus

```
                                                                    10:07

                          RAIL FLAW DETECTION PROGRAM

READY
                                  MAIN  MENU

            1. View/Output Ports
            2. Set window
            3. Decide flaw characteristic
            4. clock on,disable data interrupt
            5. Run the system
            6. Display Rail Flaw Data
            7. Clock off
Enter selection or <RETURN> to exit:
```

Figure B-1. Main Menu.

```
                                                                  10:00

                        RAIL FLAW DETECTION PROGRAM
 READY
                              RAIL1 MENU

Window card:                              Control card:
  Port 1 (Output): 00000000                 Port 7 (Input):  11111111
  Port 2 (Output): 00000000                 Port 8 (Input):  11111111
  Port 3 (Output): 00101100                 Port 9 (Input):  11111111

Analog Interface Card:                    Not Used Card:
  Port 4 (Input):  11111111                 Port 10 (Input): 11111111
  Port 5 (Output): 00111100                 Port 11 (Input): 11111111
  Port 6 (Input):  11111111                 Port 12 (Input): 11111111
                                 Current data
        1: 0    2: 0    3: 0    4: 0    5: 0    6: 0    7: 0    8: 0    9: 0
 10: 0  11: 0   12: 0   13: 0   14: 255 15: 255 16: 255

                              Press 0 to output
```

Figure B-2. System input and output port signal values.

10:09

RAIL FLAW DETECTION PROGRAM

READY

RAIL2 MENU

1. 0 degree window delay
2. 0 degree window width
3. 90 degree window delay
4. 90 degree window width

enter selection or <return> to exit:

Figure B-3. Timing window widths and delays.

```
                                                              10:11

                    RAIL FLAW DETECTION PROGRAM

READY
                         RAIL3 MENU

input dtflag:0
input thhold1:100
input thhold2:
input thhold3:
input thhold4:
input thhold5:
input thhold6:
input thhold7:
input thhold8:
input thhold9:
```

Figure B-4. Alarm threshold settings.

APPENDIX C

Examples of strip chart recordings and computer printouts at various small flaws in Section 10 of the FAST track.

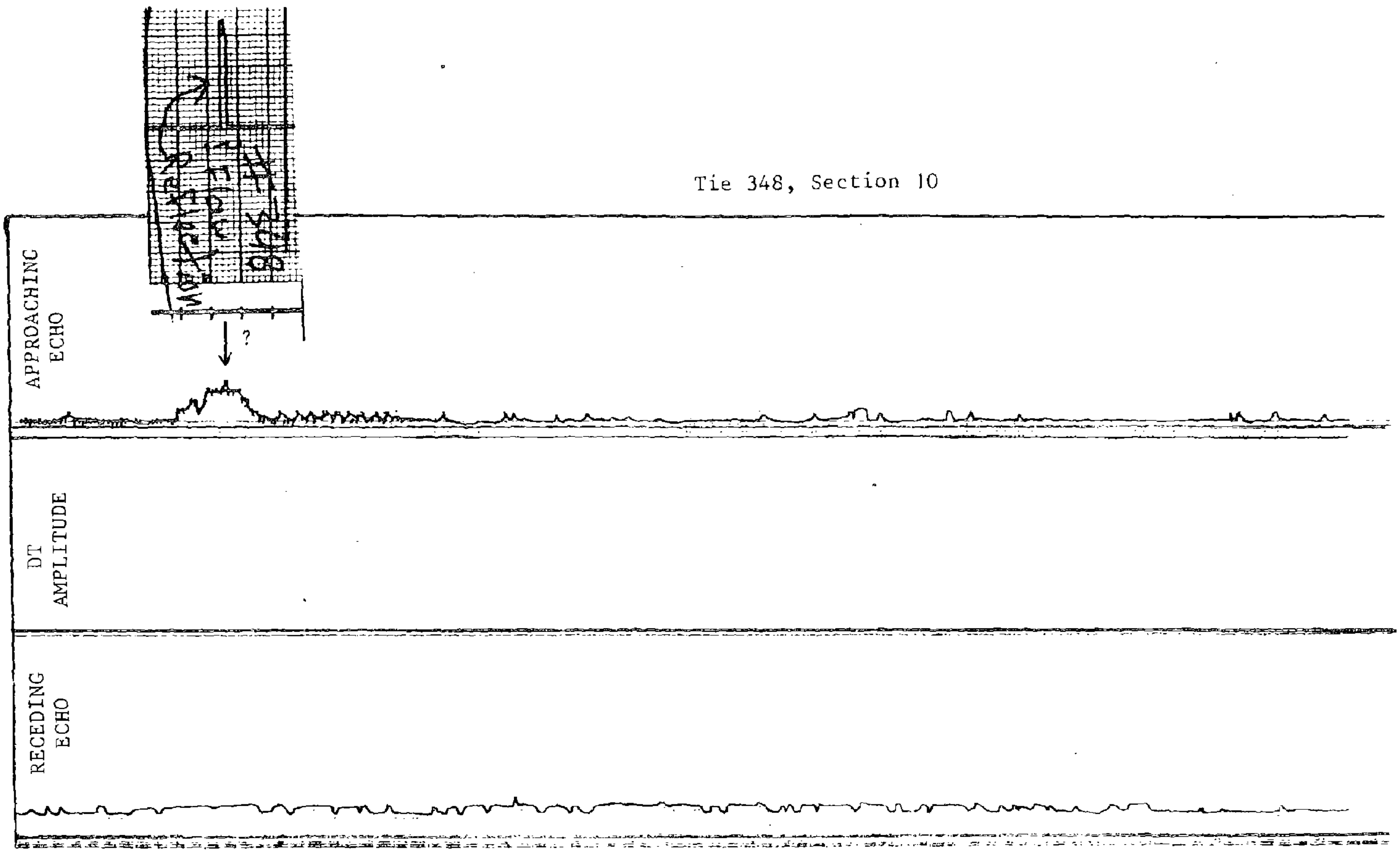


Figure C-1. Unknown echo from unexpected "flaw" in the rail head at Tie 348.
(Seen only in the approaching channel.)

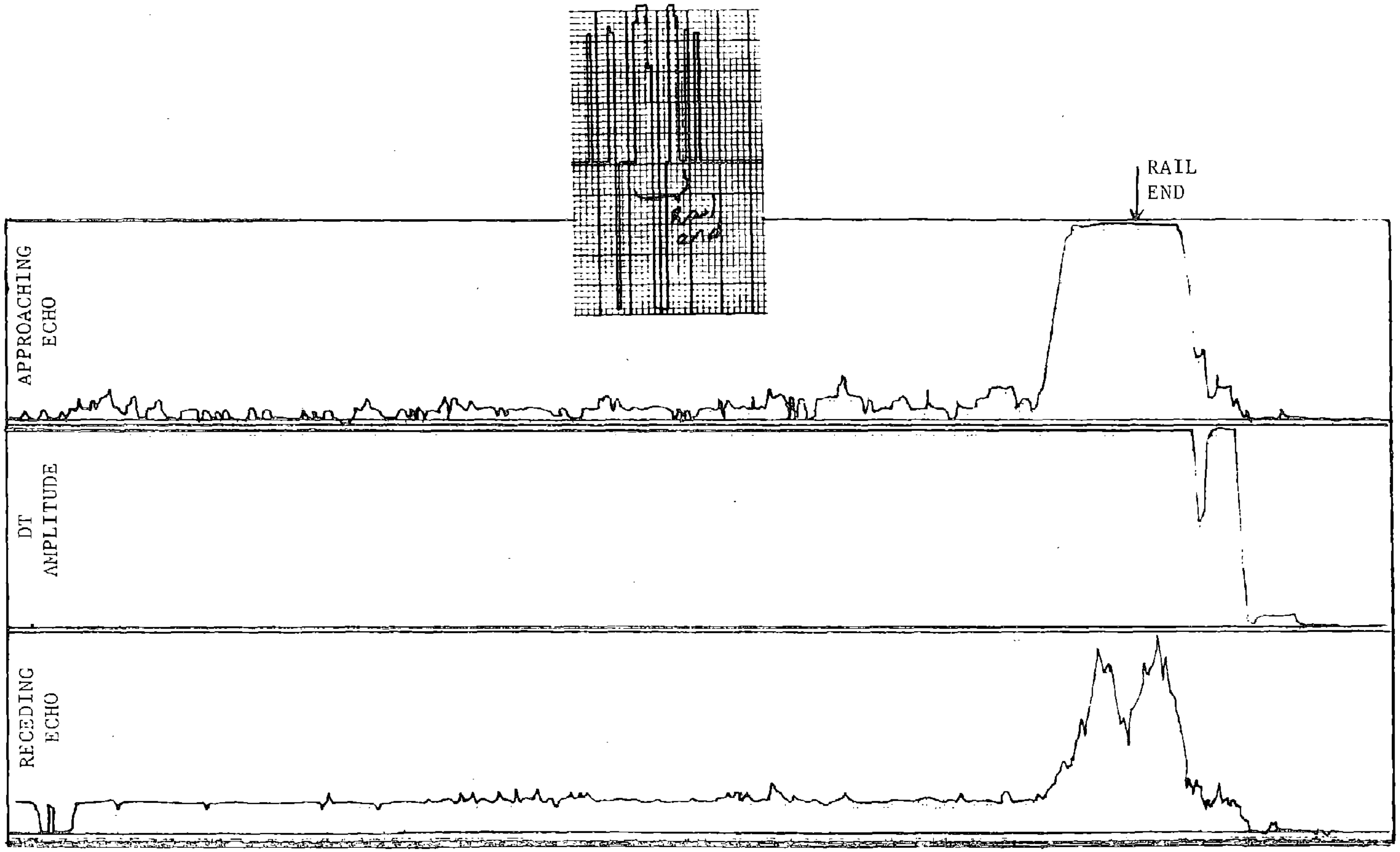


Figure C-2. Response of 90° EMAT to a flaw in the head of the rail at Tie 463 near a rail end.

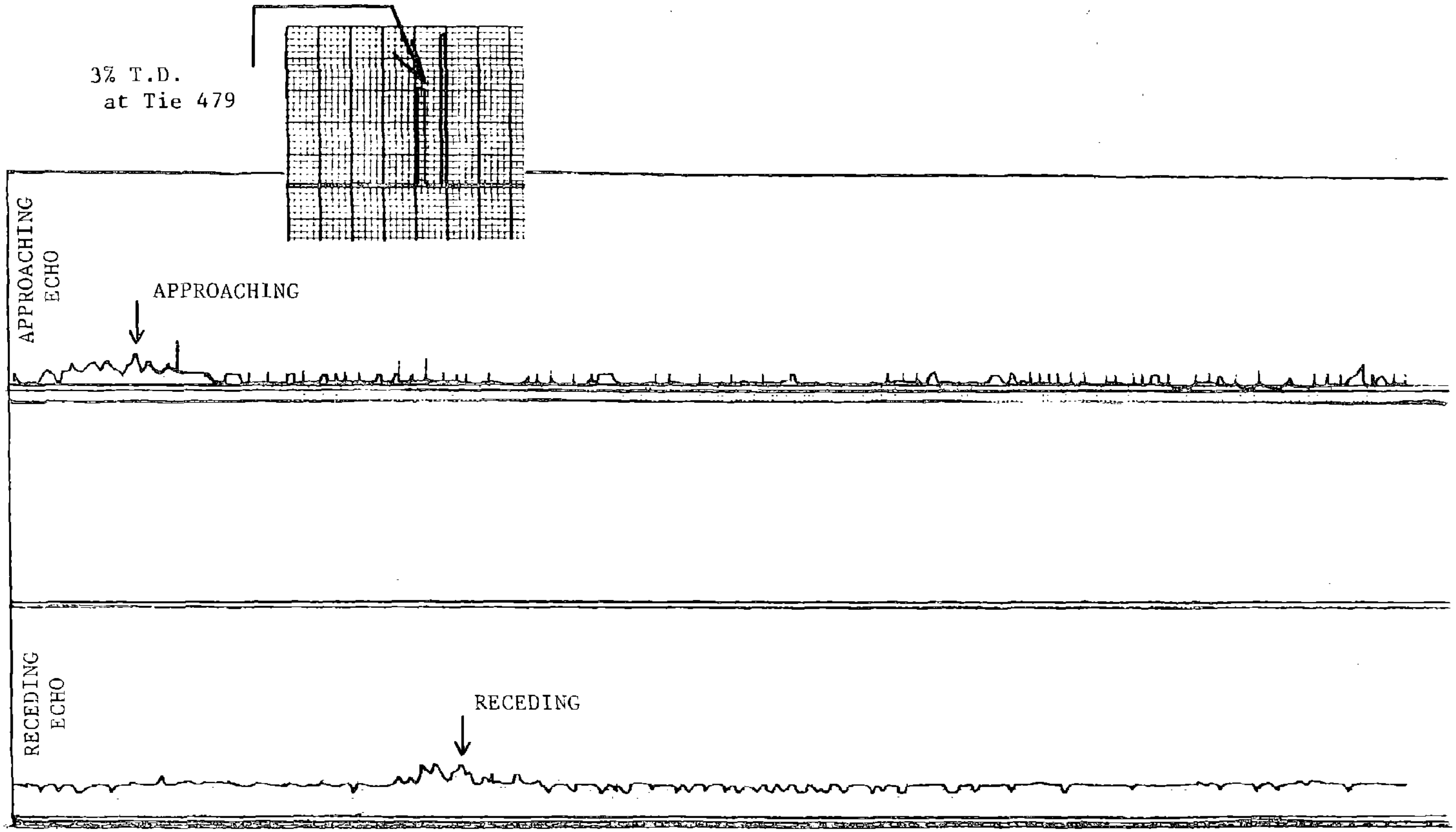


Figure C-3. Response of the 90° EMAT to a 3 percent transverse defect at Tie 479. Flaw detected in both the approaching and receding channels.

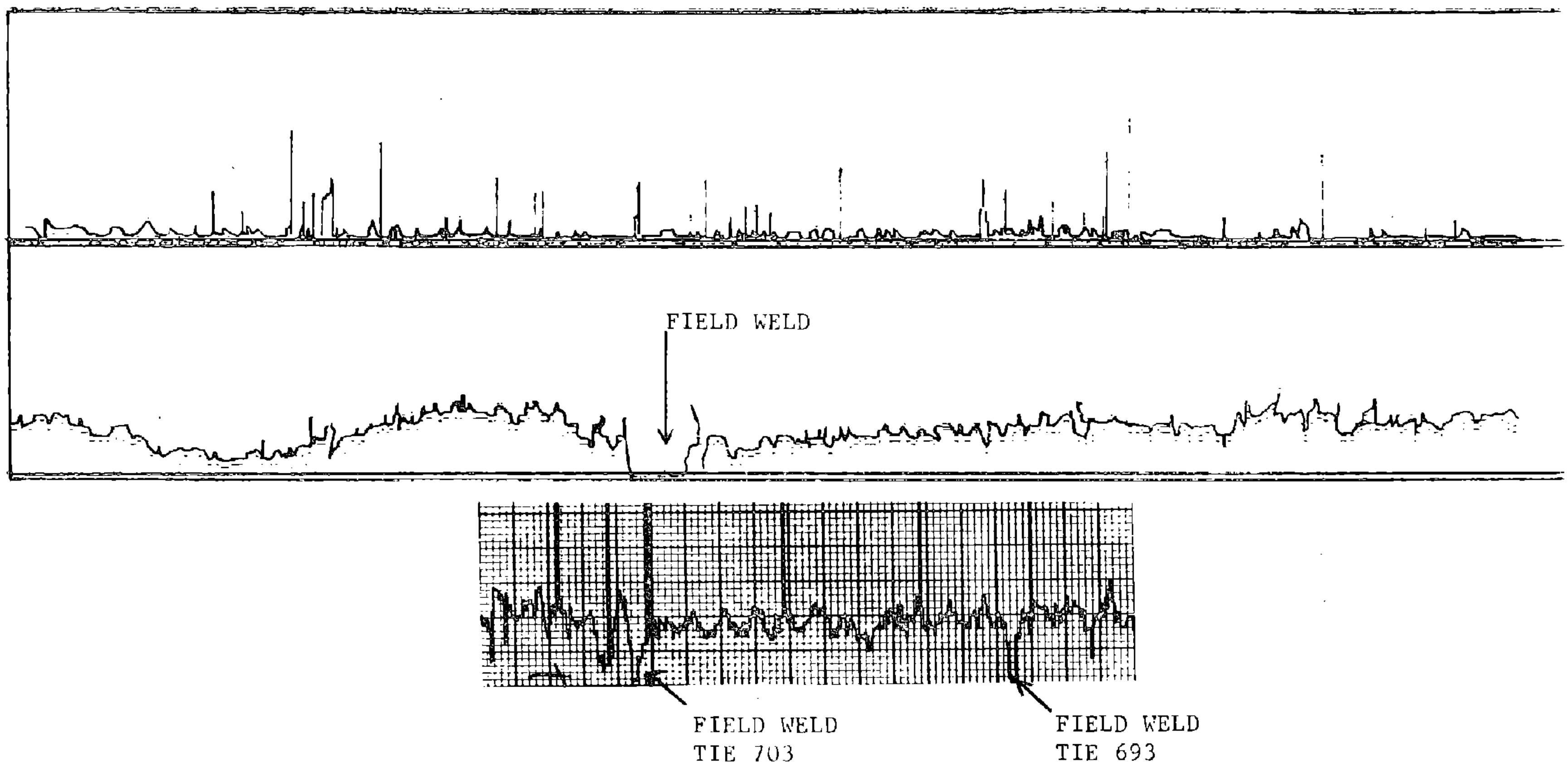


Figure C-4. Response of the 0^{o} EMAT channel to a field weld at Tie 703. The strip chart record displays a similar weld at Tie 693.

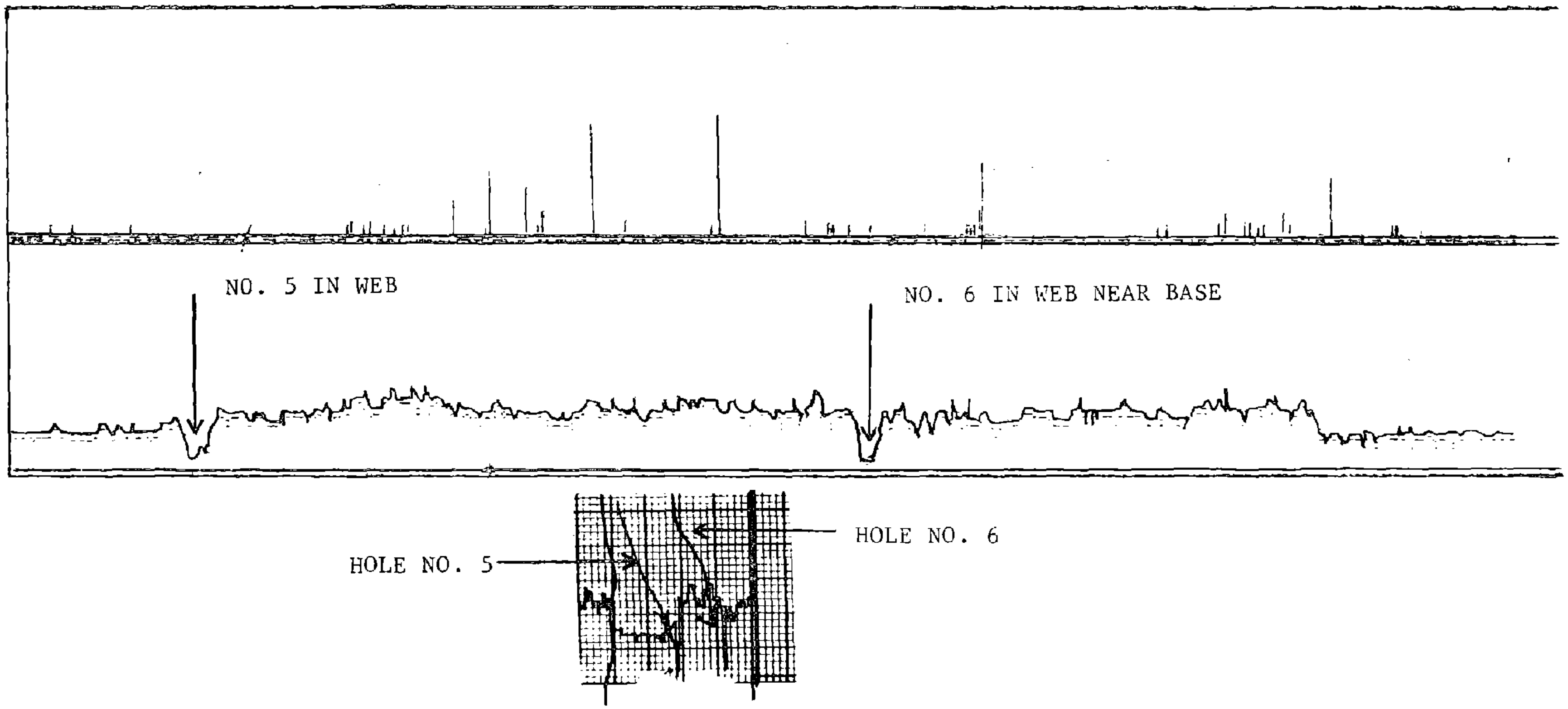


Figure C-5. Response of the 0° EMAT channel to two holes drilled in the web of a rail.

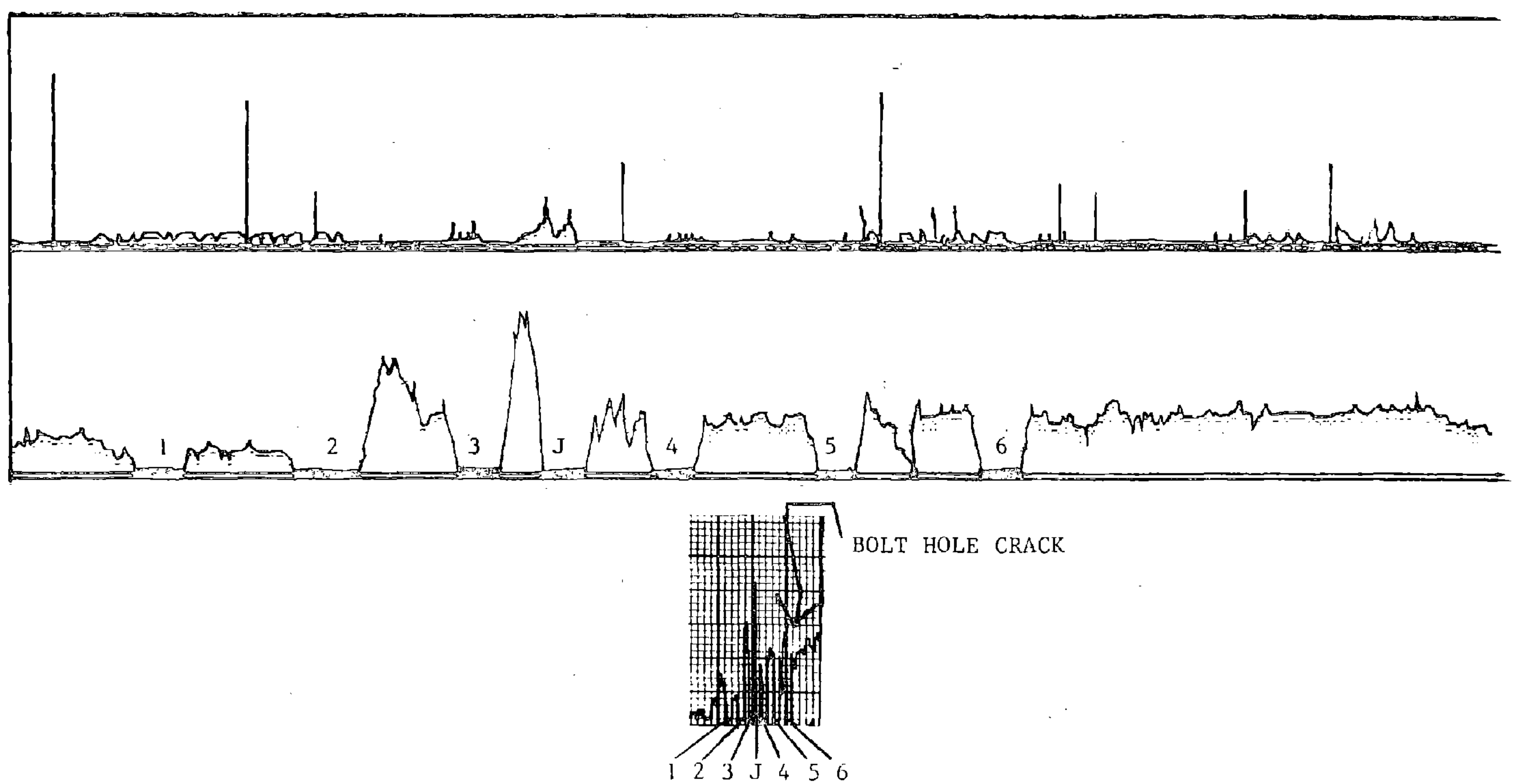


Figure C-6. Response of the 0^{o} EMAT channel to a row of bolt holes on either side of a rail joint. Bolt hole No. 2 appears larger than normal and hence may be cracked.

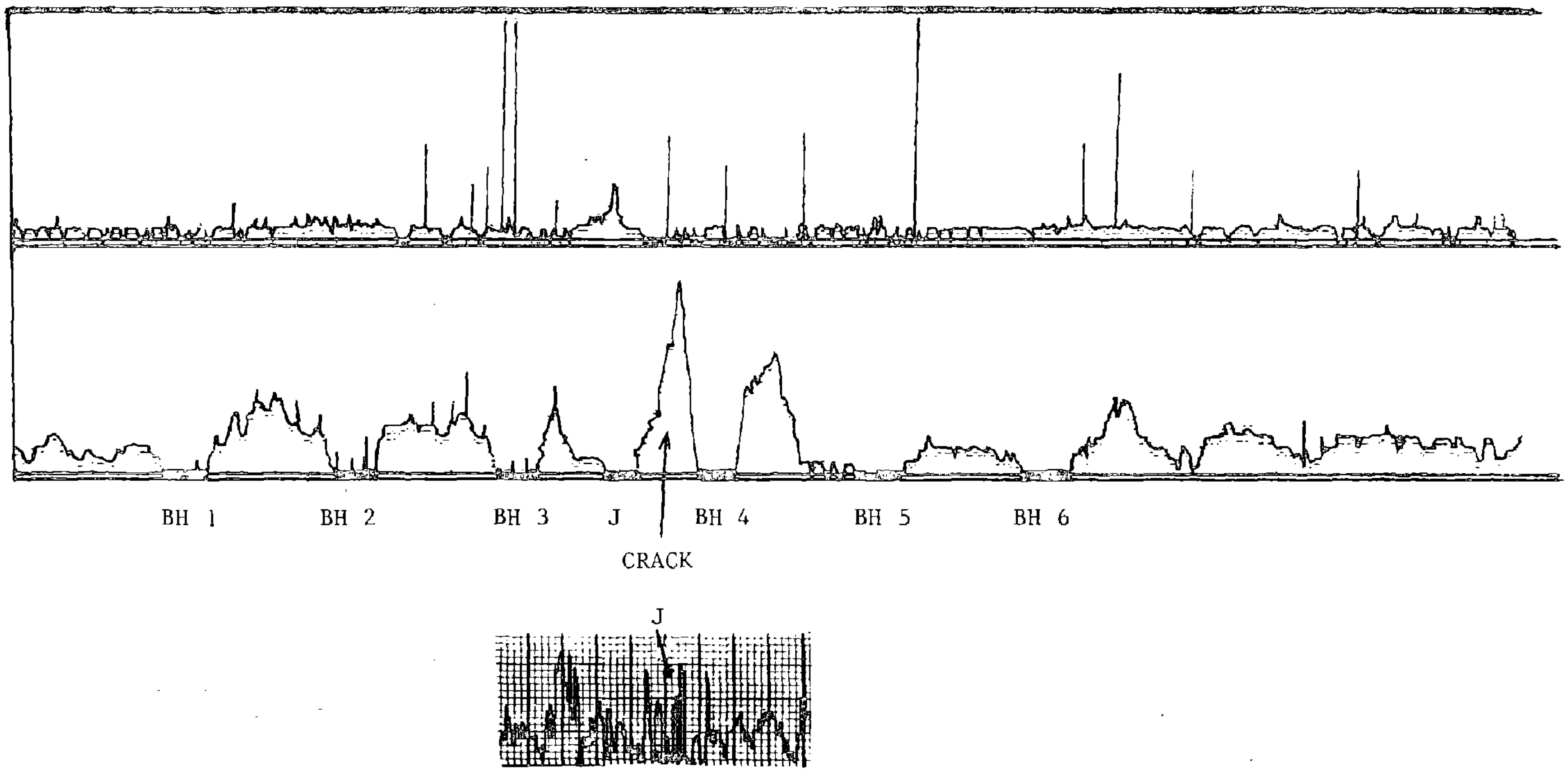
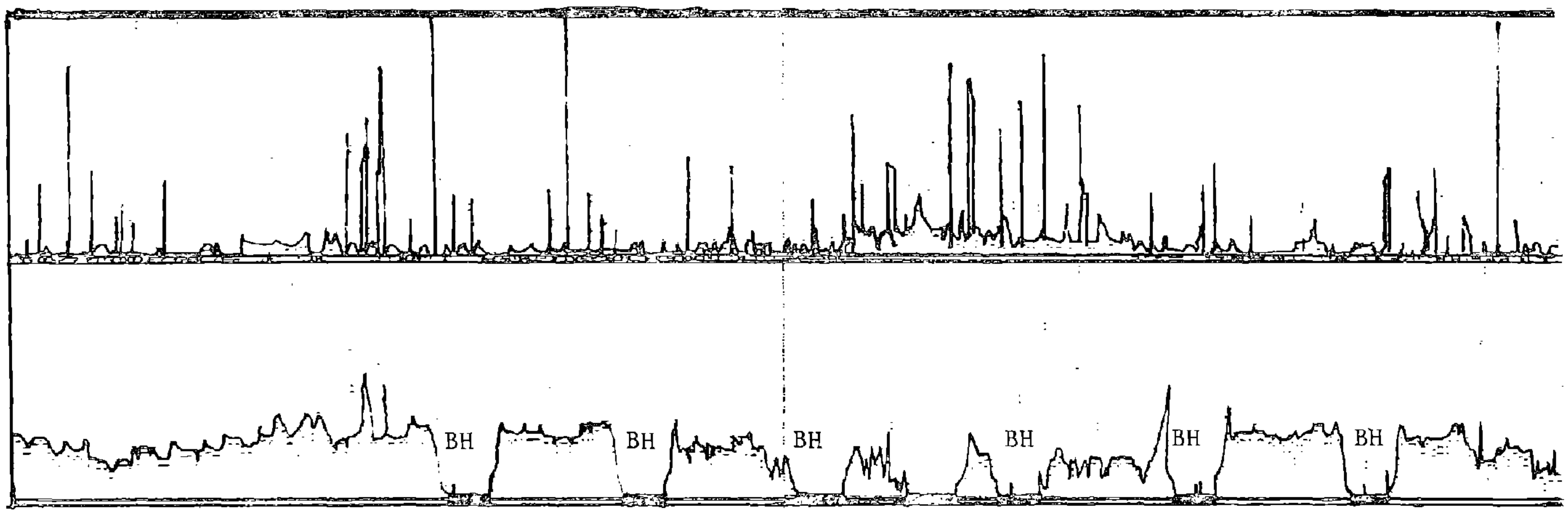


Figure C-7. Response of 0^{o} channel to the bolt holes and joint at Tie 580. Bolt hole No. 5.appears to have a crack.

Tie 724, Section 10



TIE 724
HEAD-WEB
SEPARATION

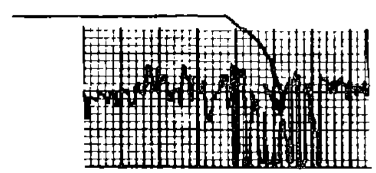


Figure C-8. Detection of an echo in the 0^{o} EMAT channel that was associated with a head-web separation at the joint near Tie 724.