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16. Abstract

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NOMENCLATURE

$Z1k$, ($Z2k$)	Voltage level in frequency channel k, obtained from signal from wheel 1(2)
SD	$\sum_k \lvert Z1k - Z2k \rvert$, except for channels with common resonances and one channel above and below common resonances
NC	Number of channels with common resonances
DI	$C_1 SD - C_2 NC$ + constant, where C_1 and C_2 are constants (Difference Index)
%	Symbol used to indicate that a given variable has been normalized with respect to the complete spectrum
N_g (x)	Number of good wheels having DI = x
N_{gT}	Total number of good wheelsets
m_g	Median DI value for good wheelsets
σ_g	Standard deviation of DI values for good wheelset population
N_B (x)	Number of cracked wheels having DI = x
N_{BT}	Total number of cracked wheels

m_B	Median DI value of cracked wheels
σ_B	Standard deviation of DI values for cracked wheels

1. HISTORICAL REVIEW AND GENERAL DESIGN CONSIDERATIONS

1.1 Introduction

This report is a description of the Acoustic Signature Inspection (A.S.I.) system for railroad wheels developed and tested for the Southern Pacific Transportation Company (S.P.), the Association of American Railroads (A.A.R.) and the U.S. Federal Railroad Administration (F.R.A.). The work was undertaken by CRC-Bethany International with help from the Southern Pacific and the University of Houston between 1980 and 1983. In 1984 CRC-Bethany sold its interest in the project to Acoustic Systems Incorporated who completed the work. The requirement is to inspect wheels on moving trains from a convenient wayside location, automatically and continuously, and with minimal interference to normal operations. In particular, the number of false alarms should be kept to a minimum. The main failure categories which need to be found (based on 1979 costs) are broken plates, broken rims, broken flanges and loose wheels. The concept of using acoustic signals for wheel inspection was the subject of an earlier feasibility study carried out at the University of Houston (U.H.) (1)

A system consisting of an automatic hammer, a microphone, a real-time spectral analyzer (R.T.A.) and a computer was tested in the laboratory and defective wheels could be distinguished from good ones. An important conclusion was that the best detection method consisted of a comparison of sounds from the paired members of a given wheelset. The acoustic signature is dependent on the wheel type, size, load, wear and surface condition, but since wheels are mounted and changed in pairs they should have the same signature; thus a significant difference in the signatures from members of a wheelset should indicate the presence of a defect or an unusual condition in one of the wheels. In order to characterize these differences in sound, a quantity termed the difference index (DI) was computed. When the DI value was greater than a certain discrimination level an alarm was declared. The study concluded with some preliminary field tests in which cracked wheels were detected on short consists. These demonstrations were encouraging, but the question arose as to how well the system would work with a larger statistical sample. Arrangements were made for a six-week period of testing in the Englewood Switching Yard of the Southern Pacific in Houston (2). The system was operated in real-time and tape recordings were made to serve as a data base for finding an algorithm which could adequately distinguish wheelsets with a defective member. No dangerously defective wheels were found during the testing period and so, for comparison purposes, some defective wheels were tested in the laboratory. One of the most interesting results was the finding that the preponderance of wheelsets with high DI values observed in the yard showed a characteristic shifting of resonance frequency values. It was postulated that this was probably due to differential wheel wear.

Following the Englewood Yard test, the FRA funded a testing and evaluation project as part of their program for the Wayside Detection Facility, at the Transportation Test Center (T.T.C.) at Pueblo, Colorado. The results of these tests have some important implications for the design of an operating system so it is appropriate to review the highlights here. Further details may be found in reference (3).

1.2 T.T.C. Tests

A consist was assembled, including six standard freight cars, a locomotive, and a specially modified truck for plate cracked wheels. This consist is illustrated in Fig.1.1; more detailed information on the wheel conditions is given in reference (4). The only wheels with real cracks were those with plate cracks (axles 31 and 32). The other defects were saw cuts, which differ from real cracks both in mechanical damping and local stress distribution. Thermal cracks usually occur in profusion on a wheel, but the defects were simulated by one saw cut per wheel.

Certain improvements were made to the system to facilitate performance of the tests. Of particular note was the replacement of the ACI wheel presence indicators with Honeywell

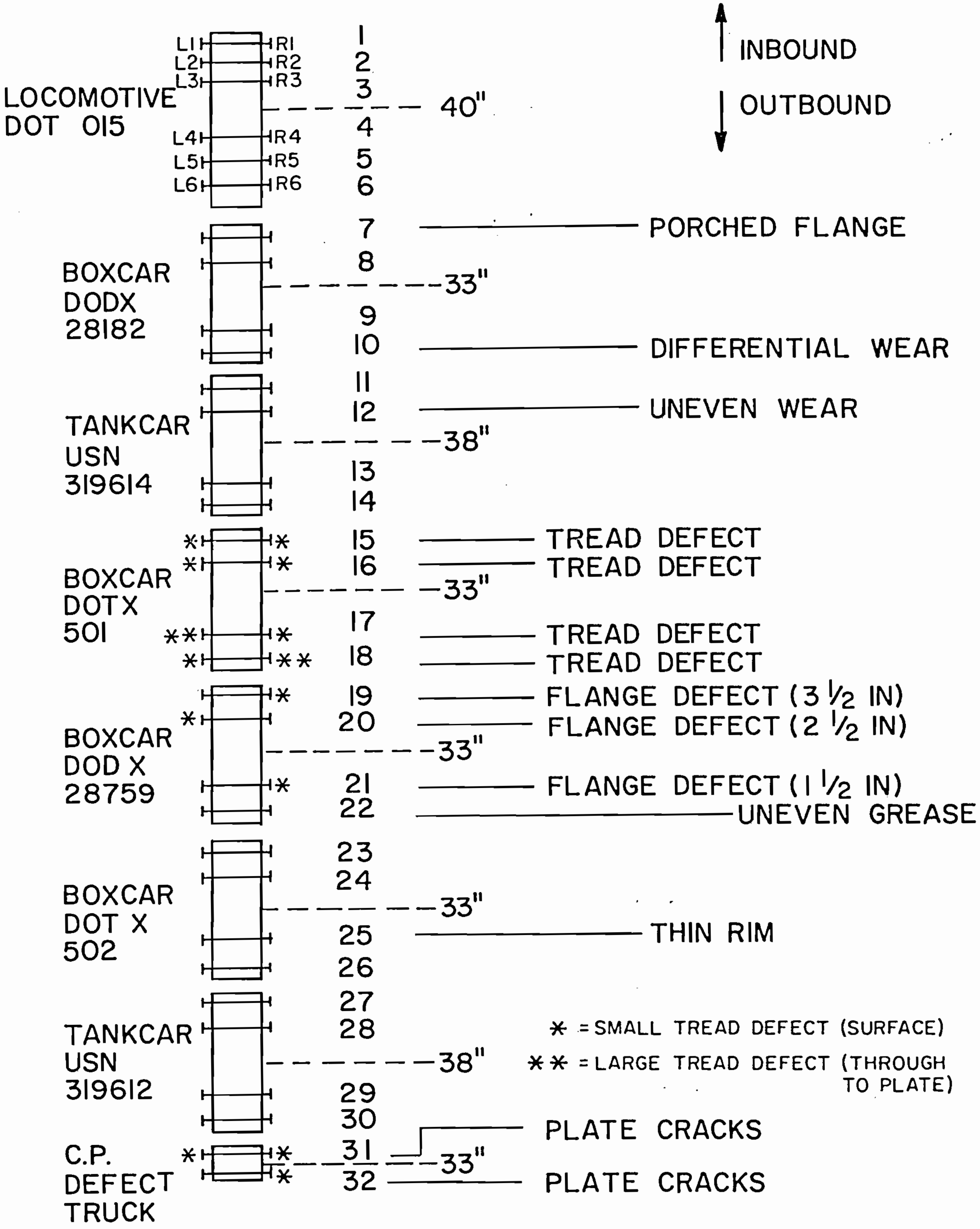


FIGURE 1.1 T.T.C. TEST CONSIST

wheel presence indicators, whose sensitivity was easier to adjust, thus avoiding the problem of missed trigger pulses which could lead to erroneous wheel counting. Reconfiguration of the system was carried out to prevent cross-talk between the microphones. The final configuration is shown in Fig.1.2 including a new timing and audio switching circuit designed to ensure that if a wheel presence pulse was missed, it would not cause incorrect wheel counting. The RTA operated in a "free-running" mode i.e., it was not synchronized with the acquired signal and this was recognized as a significant source of data uncertainty. An auxiliary timing circuit was built to attempt to correct this, but there was still an uncertainty of up to 50 m/sec in the start of the sampling time.

A problem with the speed of data storage to diskette was also encountered; it was believed to lie in the software and was not a fundamental limitation to the system. Another speed limitation of the system arose from the action of the hammer, which was activated when a wheel flange depressed a plunger linked mechanically to the impacting arm. Consequently, the impact force depended on the train speed. In turn this caused the sound pressure level generated at the microphone to depend on the train speed. In order to keep the received signal within the dynamic range of the RTA, the settings of the instrumentation had to be changed when the speed of the consist was changed. A series of calibration runs was made to determine the optimum values of these settings. The slow speed of the

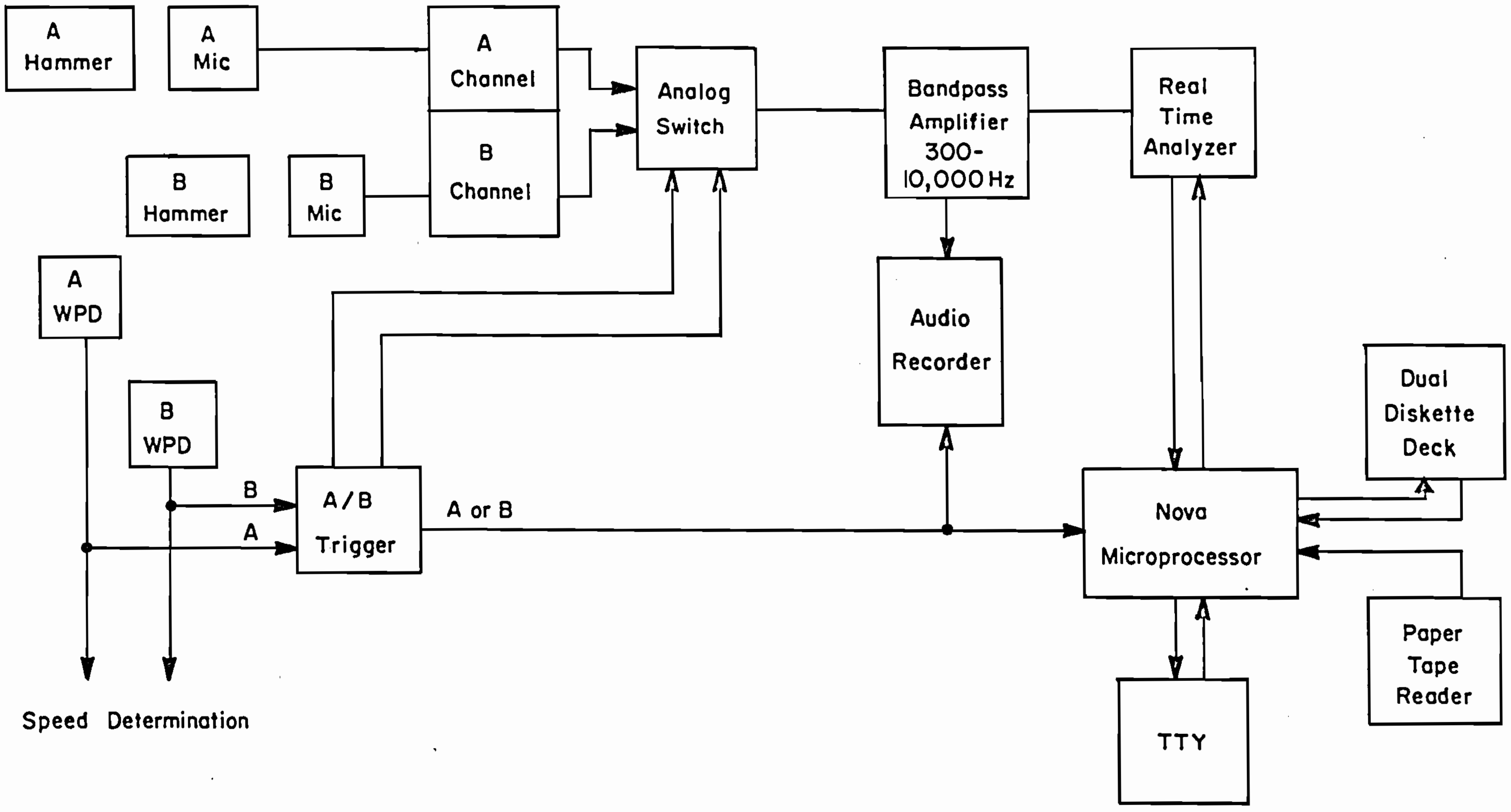


FIGURE 1.2 BLOCK DIAGRAM OF THE A.S.I. SYSTEM FOR T.T.C. TESTS

teletypewriter used for input and output made data processing a tedious task.

1.3. Analysis Of T.T.C. Data Using Difference Index

The DI algorithm used in the U.H. program having been used to collect data from in-service wheels (2), it was decided to investigate first how this algorithm performed against the T.T.C. consist. A major feature of the DI algorithm is in recognition of "common" resonance peaks, i.e., the number of resonances occurring at the same frequency in both wheels. However, because of the finite frequency bandwidth of the RTA, some peaks are not always counted in the same frequency channel. The FRA project staff therefore expanded the definition of "common" resonances to allow for shifts of two channels.

The performance of a detection algorithm depends on the sample of wheels available. The T.T.C. consist was not a statistical representation of wheels encountered in service. Since the only available data sample with in-service wheels was that obtained during the Englewood Yard test (2) it was decided to re-run the diskette recorded data from the Englewood test through the revised computer program for DI. The resulting histogram of DI values is shown in Fig.1.3 and median values for the Test Consist are shown in comparison. Four wheels from the Englewood sample would have been flagged by the new program, if the

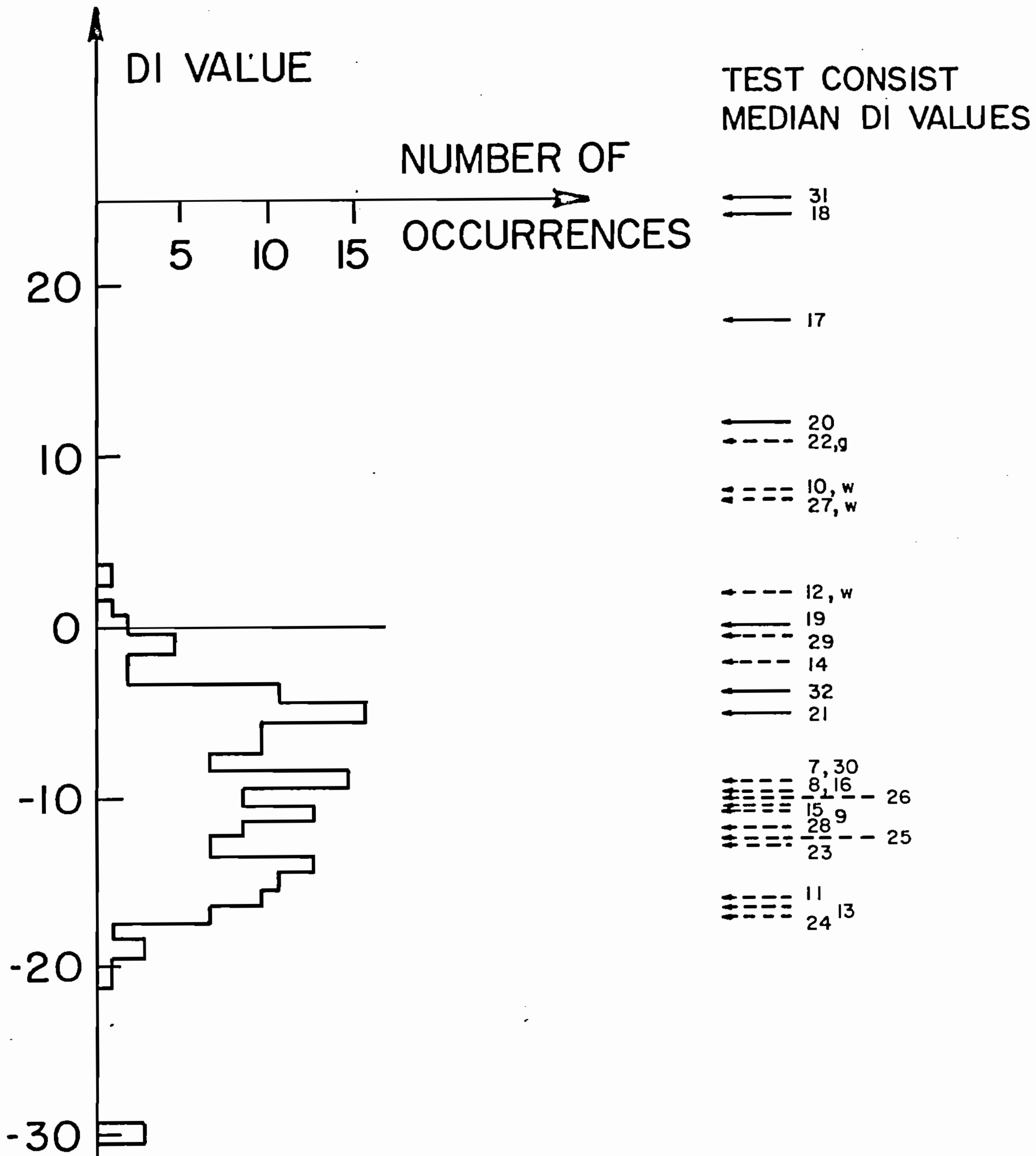


FIGURE 1.3

HISTOGRAM OF DI VALUES FROM ENGLEWOOD YARD DATA USING IMPROVED PROGRAM, COMPARED WITH MEDIAN DI VALUES FOR TEST CONSIST USING IMPROVED PROGRAM. SOLID ARROW INDICATES CRACKED OR BROKEN FLANGE. g: GREASY w: DIFFERENTIAL WEAR discrimination level had been set at zero. Since a detailed examination of the wheels sampled during the Englewood test was not possible, there was no information on the actual condition of these wheels, but the probability was that none of them were dangerously defective. It should be noted that the four wheelsets on the Test Consist with the highest DI values were axle 31, with a plate cracked wheel, axles 17 and 18 with "calamity" tread defects and axle 20 with a 2-1/2 in. flange cut. All of these wheels had DI values well above the highest value in the Englewood sample.

1.4. Estimate Of False Alarm Rates With DI Algorithm

If, for the T.T.C. sample, the discrimination level were set at DI = 11.5, axles 31, 18, 17 and 20 would be declared bad, with a zero false alarm rate. However, if the discrimination level were reduced to DI = 0, only one more wheel, on axle 19 would be found and false alarms would result from axles 22, 10, 27 and 12. The false alarm rate (FAR) would then be 4/9, for the T.T.C. consist. Finally, if the discrimination level were reduced to DI = -5, defective axles 32 and 21 would also be detected, so that all defective wheels would alarm, but with additional false alarms on 29 and 14, to give FAR = 6/13 for the T.T.C. Consist. However, it is clear that DI = -5 is well into the population of good wheels, as represented by the histogram, so that the FAR would then be much greater for in-service wheels.

In order to estimate how well the algorithm would perform in the field the two wheel populations must be normalized. Assume that the populations of good wheels can be represented by Gaussian distributions:

$$N(x) = \frac{N_T \exp\left[-(x-m)^2 / 2\sigma^2\right]}{\sigma\sqrt{2\pi}} \qquad (1.4.1)$$

In order to fit numerical values to these distributions information on the number of cracked wheels has to be obtained. Most cracked wheels are presently found by visual inspection, although some still elude inspectors and cause derailments. In order to determine the number of cracked wheels found by inspection an inquiry was made of the AAR's Car Maintenance Cost (CMC) Data Base (4). For the railroads participating in the CMC Data Base, wheel caused derailments are available from the FRA Accident Data Base. These statistics, for 1980, covered 19.8% of the U.S. car fleet, representing approximately 1,347,000 wheelsets.

Using these statistics:

N_{BT} = total of wheel failures (Why Made Code Numbers 66, 68, 71 and 83)

+ total broken wheel caused accidents

= 853 + 24 = 877

N_{gT} = (total number of wheelsets in fleet)

(number of wheelsets with a cracked member)

= 1,347,000 - 877

= 1,346,123

Means and standard deviations for the two populations are estimated from the numbers in Fig. 1.3:

m_g = 10.1

m_B = median DI for wheelsets 31, 18, 17, 20, 19, 32, 21

= 10

σ_g = 5.55

σ_B = 12.01

Fig.1.4 shows hypothetical Gaussian distributions fitted to these parameters. By integrating the area under the two curves it can be shown that for a discrimination level of DI = 4.5 the false alarm rate would be 0.91 and the detection rate 0.672. If the wheels missed by the inspectors are uniformly distributed among the types of cracked wheels, this would represent a savings of 0.672 of the accident costs. Increasing the discrimination level to DI = 10 would lower the false alarm rate to 0.31 and the detection rate to 0.50. On the other hand, decreasing the discrimination level would increase the false alarm rate to unacceptably high values without significantly improving the detection rate.

It is clear that one way to improve the performance of the system would be to reduce the false alarm rate. The false

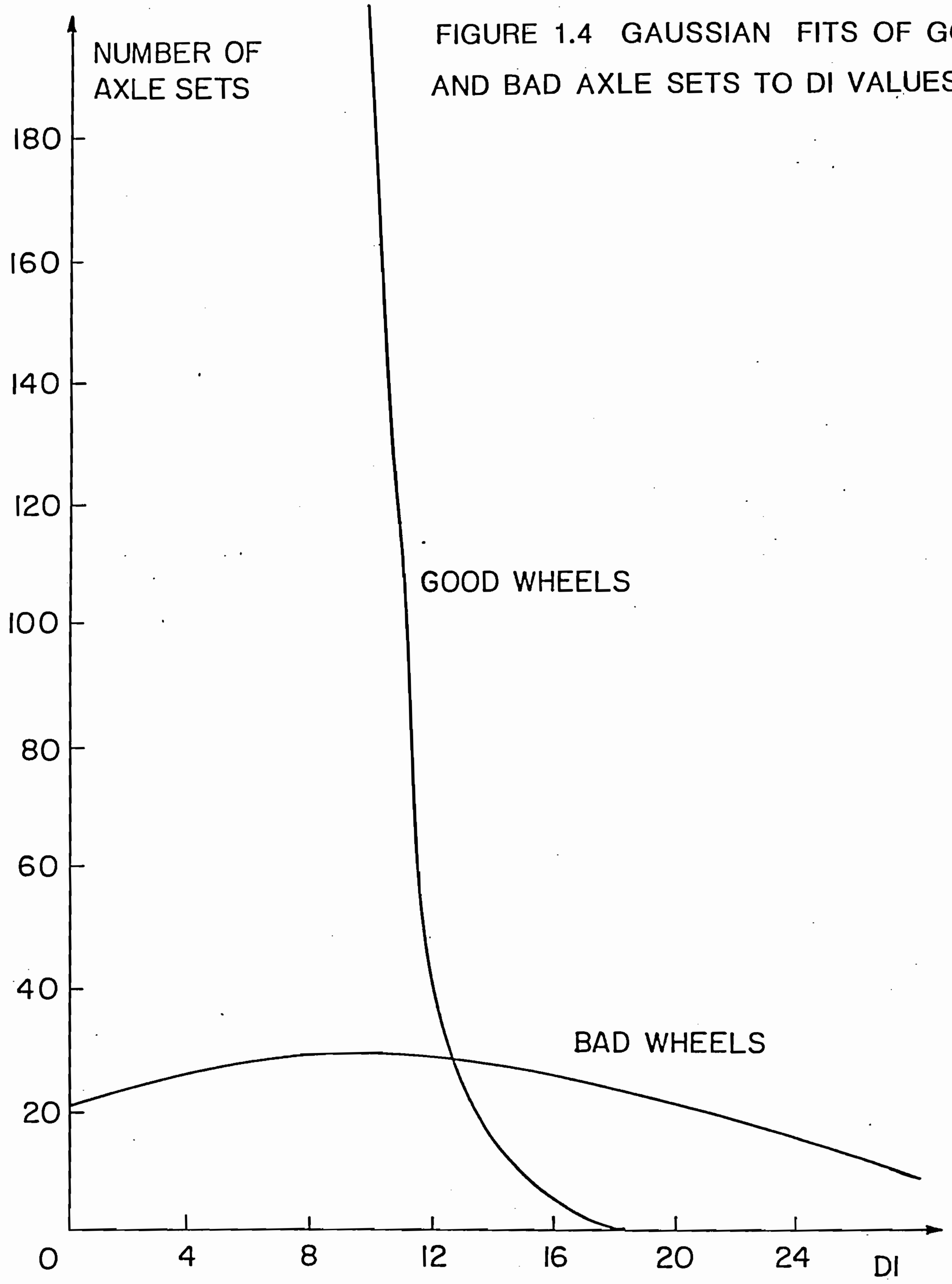


FIGURE 1.4 GAUSSIAN FITS OF GOOD AND BAD AXLE SETS TO DI VALUES
NUMBER OF AXLE SETS
180
160
140
120
100
80
60
40
20
0
4
8
12
16
20
24
DI
GOOD WHEELS
BAD WHEELS

alarms are caused by wheel conditions other than cracks causing the members of a wheelset to sound different. Two such wheel conditions, are: 1) differing amounts of grease on the two wheels, and 2) different degrees of wear. Algorithms to recognize these two conditions are discussed in the next section. Another way to improve the performance of the system would be to increase the separation of the mean values of the good and defective populations. Evidence is presented in a subsequent section that this might be done by including a "time domain" term in the DI algorithm.

1.5. Wheel Condition Algorithms

Again referring to Fig.1.3, the fifth highest DI value on the Test Consist was obtained from axle 22, which had one very greasy wheel. This condition was deliberately created by cleaning the mate wheel and is thus rather unlikely to be encountered in service. Although greasy wheels are usually indicative of a leaking journal bearing, which is an undesirable situation, the wheel itself should not be classified as defective. A new algorithm was therefore written to recognize greasy wheels, based on the fact that grease causes heavy damping at high frequencies. This discriminant was termed GI and is computed from the difference of energy in the highest and lowest quartiles of the frequency range. Details of the testing of the algorithm are given in reference (3) and it was concluded that a greasy wheel could be recognized as such by this algorithm to a highly reliable degree.

Referring once more to Fig.1.3 it may be seen that the wheelsets with the next highest DI values, after the greasy wheel, are on axles 10 and 27. Both of these wheelsets show considerable differential wear. Following the S.P. Englewood Yard study, it was predicted that this condition could be recognized by using the finding that the prominent resonance lines in the spectrum are very close to the theoretical values for flexural modes of a ring (2). An algorithm was devised to search for a resonance in the vicinity of the predicted value.

Fig.1.5 shows the resonance frequency values found by the search routine as a function of mode number. It can be seen that different wheel types fall on different curves, as might be expected. Once the software has been extended to characterize each of these curves with a single parameter, wheel type and differential wear could be added as a system output. Large differences in such a ring mode parameter among members of a wheelset might be used as an additional indicator of defects.

1.6 Time Domain Analysis

All the forms of data analysis mentioned in the preceding sections involve processing of frequency domain data. Since this data is obtained by sampling over a short time period, much information from the sound signal is, in effect, discarded.

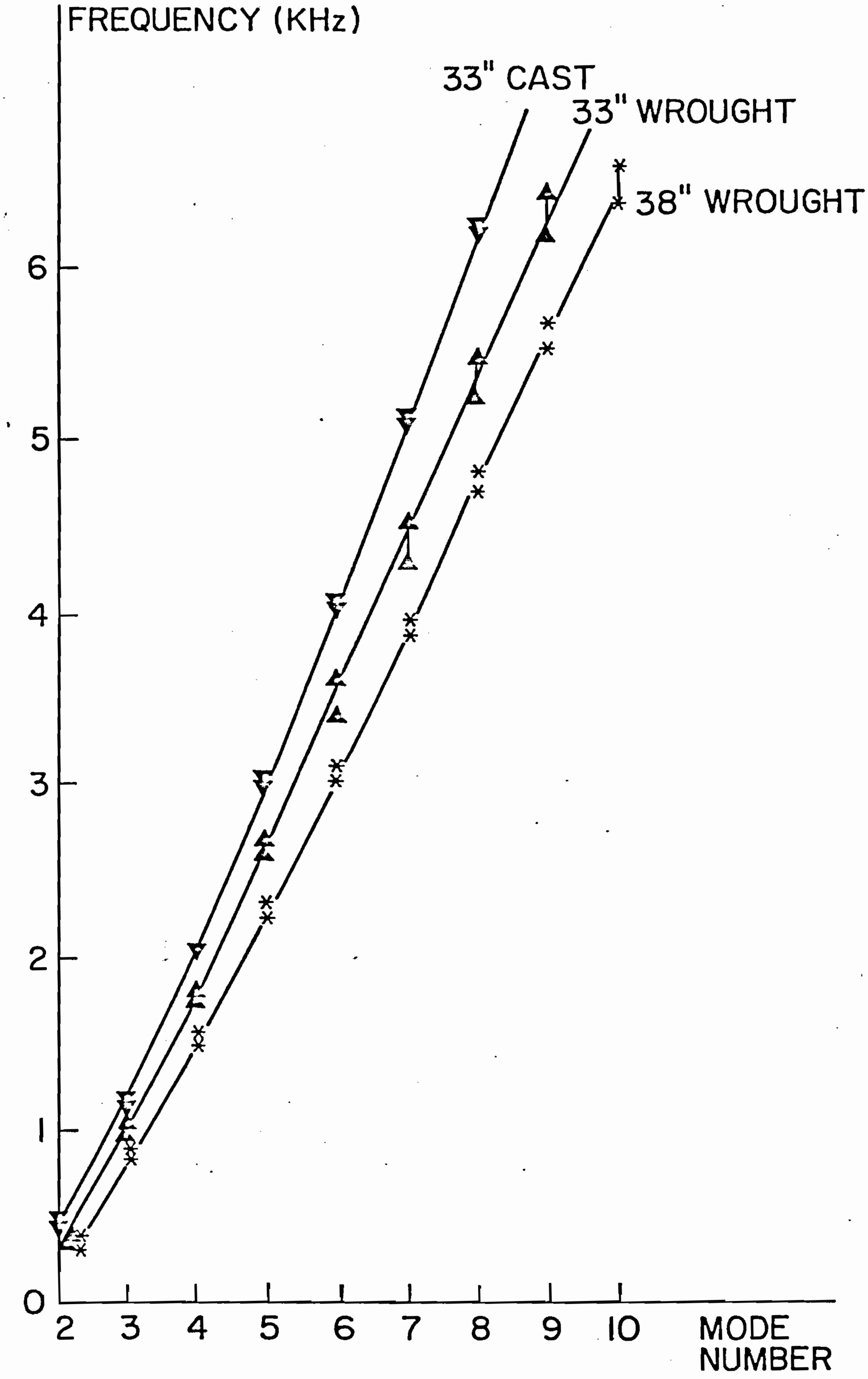


FIGURE 1.5 A.S.I. - MODE SEARCH : MODAL FREQUENCY VS. MODAL NUMBER FOR DIFFERENT WHEEL TYPES.

Early studies (1) showed that the decay of the sound with time is increased by the presence of a crack. Fig 1.6 is an oscillograph trace of a signal in the time domain. A beating effect is observed, and this is a common phenomenon. It is because of this beating that the previously mentioned 50 ms variability in the start of sampling by the R.T.A. causes a considerable variation in the amplitude of the sample. Furthermore different resonances appear to beat differently. This in turn results in lack of repeatability in the product of analysis. The physical cause of the beating phenomenon is not completely understood.

Since the U.H. system had no A/D conversion capability the only way to get an idea of the prospects for incorporating time domain terms was by "paper and pencil" studies. Oscillograph traces of the signals from all the wheels obtained in two runs were taken and two measurements made to characterize the sound from each impact:

(a) An exponential envelope fit by finding the closest match among a series of curves drawn on a template, and

(b) measurements of the "area" under each curve, using a digitizing pad and verified by checking with a planimeter.

Two indicators were then formed:

(a) DR, the difference in the decay rates of each wheel pair; and

(b) DA, the difference in the "areas" under each curve.

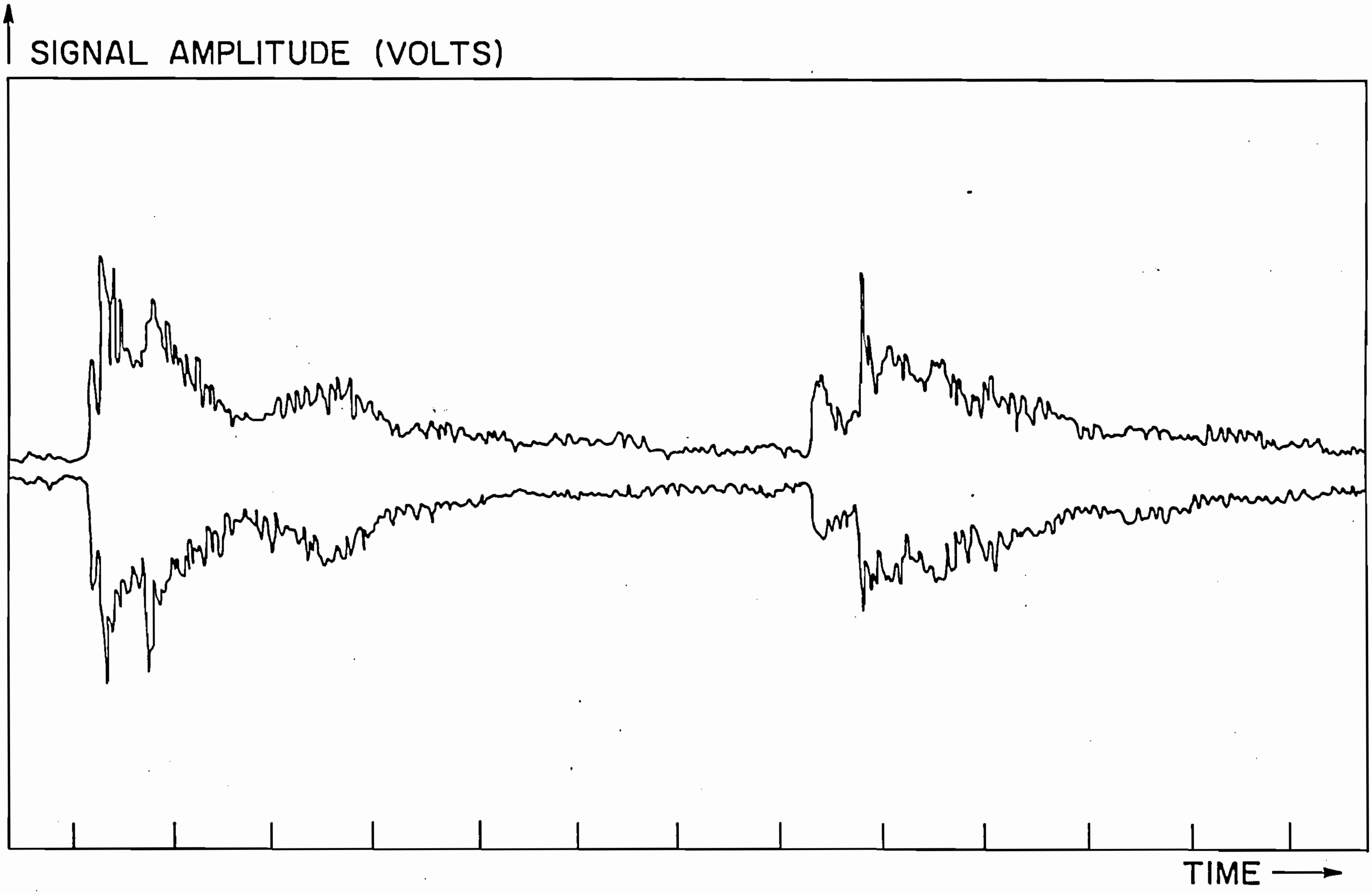


FIGURE 1.6 OSCILLOGRAPH TRACE OF TIME DOMAIN SIGNAL SHOWING BEATING (AXLE 7) (SIGNAL ENVELOPE). TIME INTERVALS: 1/10 SECOND.

Correlations between DA and DR, and between DA, DR and various frequency domain indicators were investigated. It appeared that the best result was obtained from a plot of NC% and DA (see Fig. 1.7). A discriminating line separates the "good" wheels from all the cracked wheels except for axle 21, which has a flange defect. Axle 22 is a false alarm, but would be flagged by the new GI indicator. The conclusion was that the incorporation of A/D conversion in the system either in series or in parallel with frequency analysis, could considerably improve the decision making reliability.

1.7 Location And Operating Speed Requirements

In order to decide on the optimum locations for inspection stations it is important to predicate the number of stations needed. A large number of defects are probably initiated by drag braking on steep grades (5). If this were the sole cause of defects then the required number of inspection stations would be relatively small. However, if defects do not become dangerous until the residual stress in the rim becomes tensile, or if crack growth is due to repeated load cycling then wheels may not become dangerous until long after crack initiation (6). Furthermore, some defects may be caused by faulty brakes, which do not release, or possibly by retarders (7) anywhere in the U.S. If wheels can become dangerous anywhere, then the required number of stations, I, will be given by:

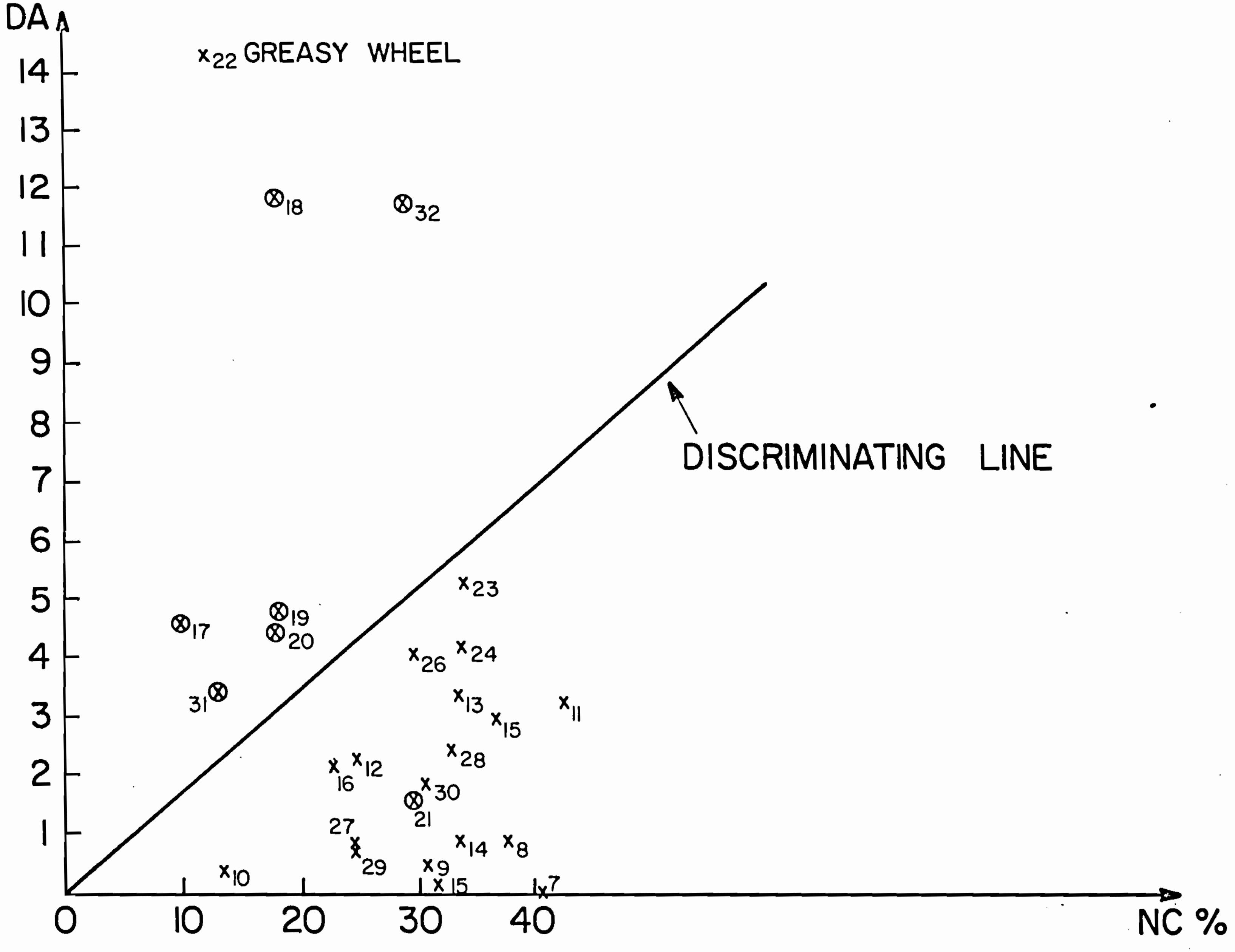


FIGURE 1.7 RECOGNITION BY COMBINING TIME DOMAIN TERM (DA) WITH FREQUENCY DOMAIN TERM (NC%). O INDICATES WHEEL WITH CRACK OR FLANGE CUT. NUMBERS REFER TO AXLES.

$$I = \frac{M}{D} \qquad (1.7.1)$$

where D is the average distance to failure after initiation of a defect, and M is the total railroad mileage or 183,055 miles (8). An estimate of D was made by Carter and Caton (9), at 350,000 cycles to failure, under a typical load, for a 0.15 inch length thermal crack in a class U or C wheel. This corresponds to:

$D = 573$ miles, for average car mileage, and
$I = 319$ stations.

This is equivalent to every wheel being inspected every 9.67 days. There are some important reservations on this estimate, and it should be regarded only as an illustration of a methodology in system design at this time.

It appears that the best location from an operational standpoint would be on the approach to a normal inspection point, such as the entrance to a yard with repair facilities to permit switching to a bad-order track with minimum inconvenience. The number of such yards in the U.S. is comparable to the predicted need for about 300 inspection points, and it is therefore assumed that systems will be designed for yard location. Location at or near a yard has the additional advantage of ready access to electric power, communication lines and track circuits. Train speed at the approach to a yard is about 15-20 mph and an interval of several minutes after passing the inspection point can be allowed before wheel condition reports would be needed. Another possible location is on the hump lead where speed is about 3-5 mph. However, wheel condition reports would then be due in 10-20 secs, after passing the inspection point. If this cannot be done and defective wheels have to be retrieved after reclassification, the cost and time involved in switching may increase by an order of magnitude. The attainment of a 20 mph operational speed for the inspection system appears to be necessary. The operational speed requirement has important design implications.

The shortest distance between wheel sets is taken to be 5 ft. Hence the shortest time interval between passage of successive axles is 170 ms at 20 mph. To achieve the best results processing should include parameters from both the frequency and time domains. For the TTC tests, for recordings made at 5 mph the time domain signal amplitude was evaluated over a 500ms interval. This interval could probably be reduced to one third without serious prejudice.

When frequency domain processing using a Fast Fourier Transform (FFT) is contemplated, the sample length required may be calculated as follows: Since the required Frequency Range is 0-7200 Hz, using the Nyquist Criterion, the sampling rate should be twice the maximum required frequency, i.e., 15,400 Hz. Hence, the sampling period should be 0.065ms. All Fourier analysis to date has been in 40 Hz wide bands. i.e.,

$\frac{7200}{40} = 180$ frequency channels were computed. It assumed that the same number of frequency bands will be adequate in performing the FFT. The same number of samples will be required in the time-domain as values in the frequency domain, i.e., 180. Hence the minimum Fourier window will be 180 x 0.065 = 11.7 ms. To improve reproducibility the signal could be averaged say 5 times, for a Fourier window of about 60 ms. The conclusion is that for adequate sampling in the time and frequency domains, a signal duration of 170ms should be sufficient.

The basic criterion for operation up to a certain speed is that the signal from one wheel should have declined to below the noise level before the start of the signal from the next wheel. This means that for the operating system, the signal duration should not exceed 170ms. But the signal duration from stationary wheel using a non-directional microphone can be as long as several hundred milli-seconds. It is therefore concluded that the microphone must either have a directivity or, if non-directional, be located so that its response will be below the noise level before the arrival of sound from a following wheel. Another important design implication is that the hammer cycle must be completed in less that 170ms. It should also be noted that the background noise from a moving train increases with speed and thus the impact force from the hammer might have to be greater than that used in the T.T.C. tests. There does not appear to be any fundamental reason why these design changes could not be accomplished and thus permit the higher speed operation.

1.8 Computational Requirements

It was concluded, as explained in the foregoing sections, that an operational system should differ from the one assembled by the University of Houston in the following major ways:
1) data acquisition should be possible up to 20 mph, with normal operation at 15 mph, (5 mph in the U.H. system),
2) the false alarm rate should be reduced, with improvements in the software,
3) the data processing time for a 100 car train should not exceed 10 minutes.

The design requirement of a higher operating speed and its consequences were explained in the preceding section. But the necessary software improvements also require hardware changes. The U.H./T.T.C. program computed the difference in the Fourier transforms of the sound from members of a wheel pair obtained from a real time analyzer. However, as pointed out in Section 1. 6, the inclusion of a measure of the decay of the signal in time should improve the discrimination of defective wheels. It was not possible to compute such terms in the U.H. system because the signal itself was not retained in memory. It was therefore decided that in an operating system, A/D conversion of the signal should be made and that this digitized record of the signal be retained to permit time domain analysis. The second recommended improvement in the software was the use of a "cascaded" decision logic to filter out good wheelsets which give rise to high DI values and thus might cause false alarms. For example, greasy wheels and wheelsets with differential wear have been identified as causes of false alarms. Algorithms to recognize these conditions should be incorporated in the software of an operating system.

The third major design change was due to the need for a short processing time. Even with the limited software of the U.H./T.T.C. system, calculation of the DI value for a wheelset took about 30 seconds using BASIC on a NOVA 1200 computer, which would take 3 hours to compute the results for a 100 car train. Clearly a much faster language and computer were necessary. To obtain an indication of the possible improvement in computing speed a test program was run on a NOVA 1200 and a Data General Eclipse. It was concluded that the old U.H./T.T.C. program could be run in less that 2 minutes on the Eclipse for a 100 car train. Although the additional inclusion of time domain terms and cascaded decision logic will increase the processing time, it is still reasonable to expect all processing to be completed within a 10 minute period. Some additional time saving would result from data acquisition, with a foreground program, and simultaneous data processing, with a background program. A computer such as the Eclipse is not suitable for a wayside location, and thus the system is conceived as shown in Fig. 1.8, with the wayside hardware located at a convenient point and data

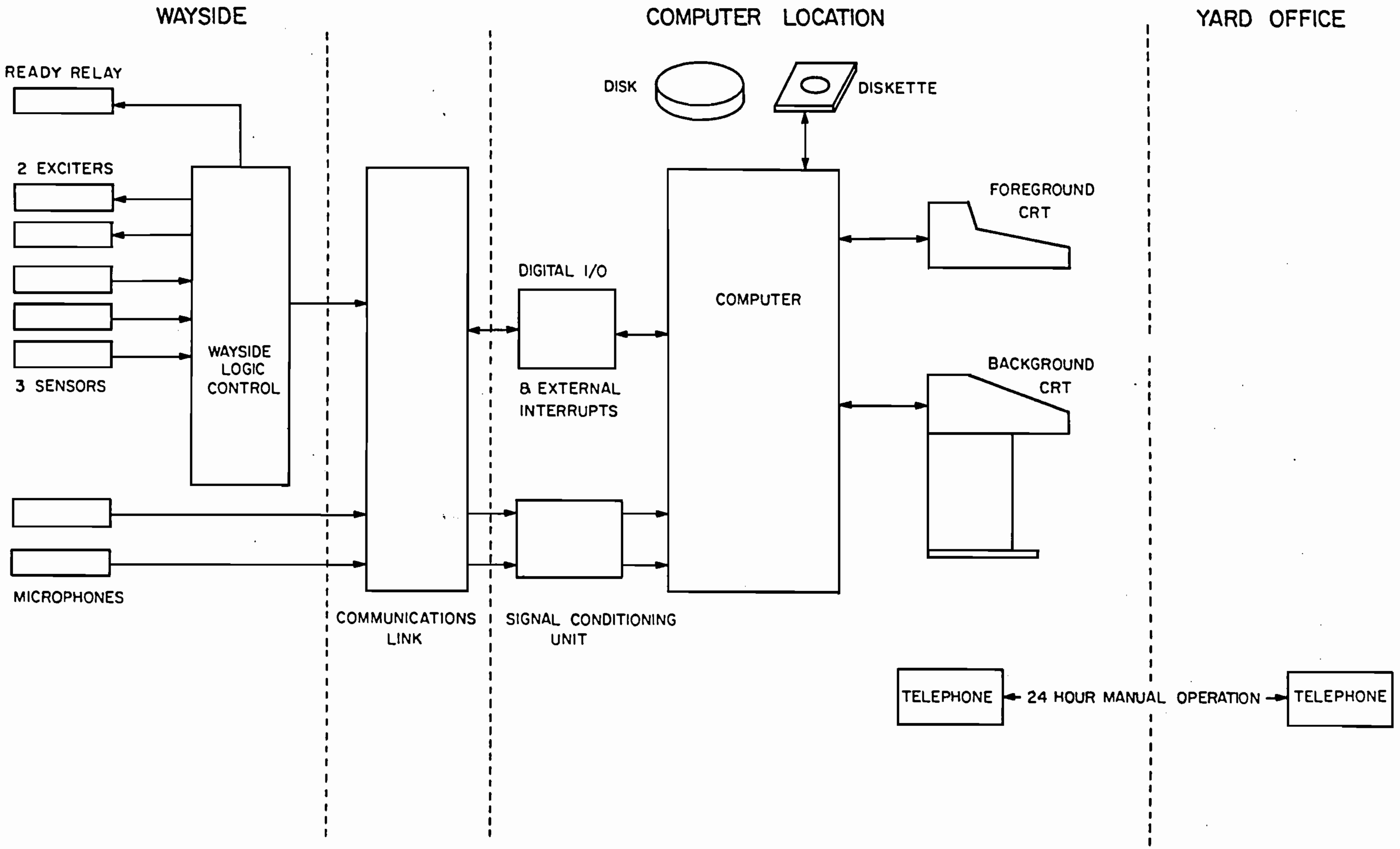


FIGURE 1.8 SCHEMATIC OF AN OPERATIONAL A.S.I. SYSTEM

and control signals handled through a communications link to a computer center.

At a sampling rate of 15,400 Hz and signal duration of 170 ms there will be 0.170 x 15,400 = 2618 samples or "words" to be stored per wheel. Although 12 bit precision (1 part in 4096) will be adequate, disk and CPU memory requirement per wheel would be 2618 X 16 = 41,888 bits. The storage of the information must be accomplished before the arrival of the data from the next wheel on the same side, or within a time period of 170ms. This corresponds to a data acquistion rate of 246,400 bits/sec. The memory required for a 200 car train with 8 wheels/car is then calculated to be 8.4 megabytes. It is possible that data processing could begin before completion of train passage, in which case these memory requirements could be reduced. Data acquisition and processing would then need to be independent functions.

As mentioned earlier, the desire to include time domain analysis leads to the idea of storing the signals, but the most compelling argument for total signal storage is that it does not constrain the use of improved signal processing techniques which might result from later research.

1.9 Site Selection

Several possible sites on the S.P.'s Houston system were considered (see Fig. 1.9). A list of requirements for the site was made and in collaboration with Southern Pacific personnel, the various possible locations were evaluated on a basis of excellent - good - fair - poor - as per Table 1.1.

The overriding concern was that the system should cause a minimum interference with normal operations. Since the design configuration proposed would not be capable of operating at above 20 mph, it was essential it not be placed at a location with a speed limit higher than this. This ruled out certain locations including the double main line close to CRC Bethany's office (Site 6).

Another important consideration was to locate the system close to a yard so that something could be done easily and quickly if a defective wheel was found. The system also had to be close to a siding convenient for parking a test consist.

The team finally devolved on the Galveston line inbound to Englewood. Some locations were found where the double track separated enough to install the microphones within clearance regulations and the final choice was dictated by the need for convenient access to telephone lines. This location (site 1) is close the Port Terminal building at 7298 Clinton Drive. There is a signal at the location and installation close to the signal is favored so that trains will be either moving on green or accelerating as they pass the installation.

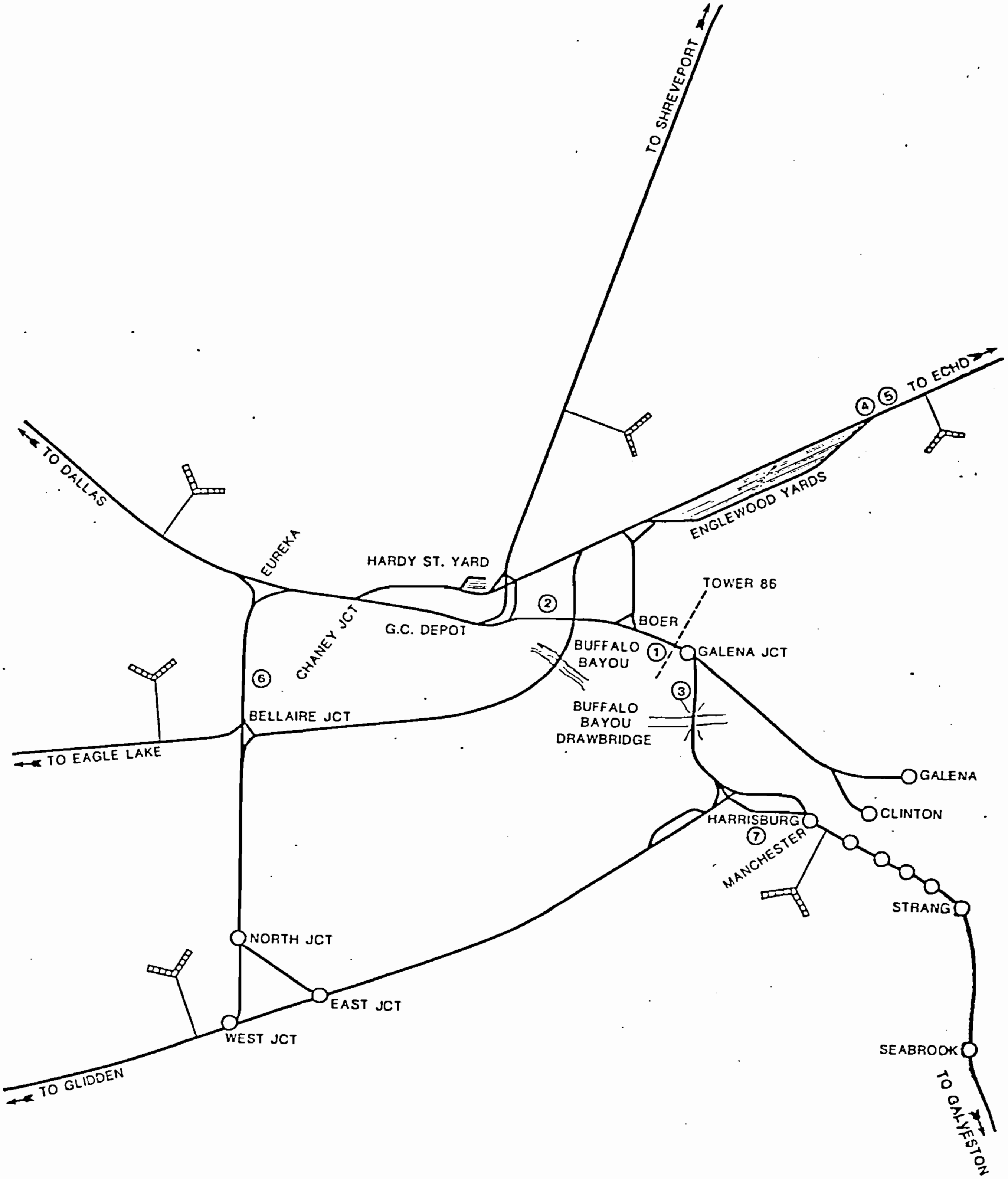


FIGURE 1.9 SOUTHERN PACIFIC HOUSTON AREA SYSTEM

C889-1085-AW

TABLE 1.1

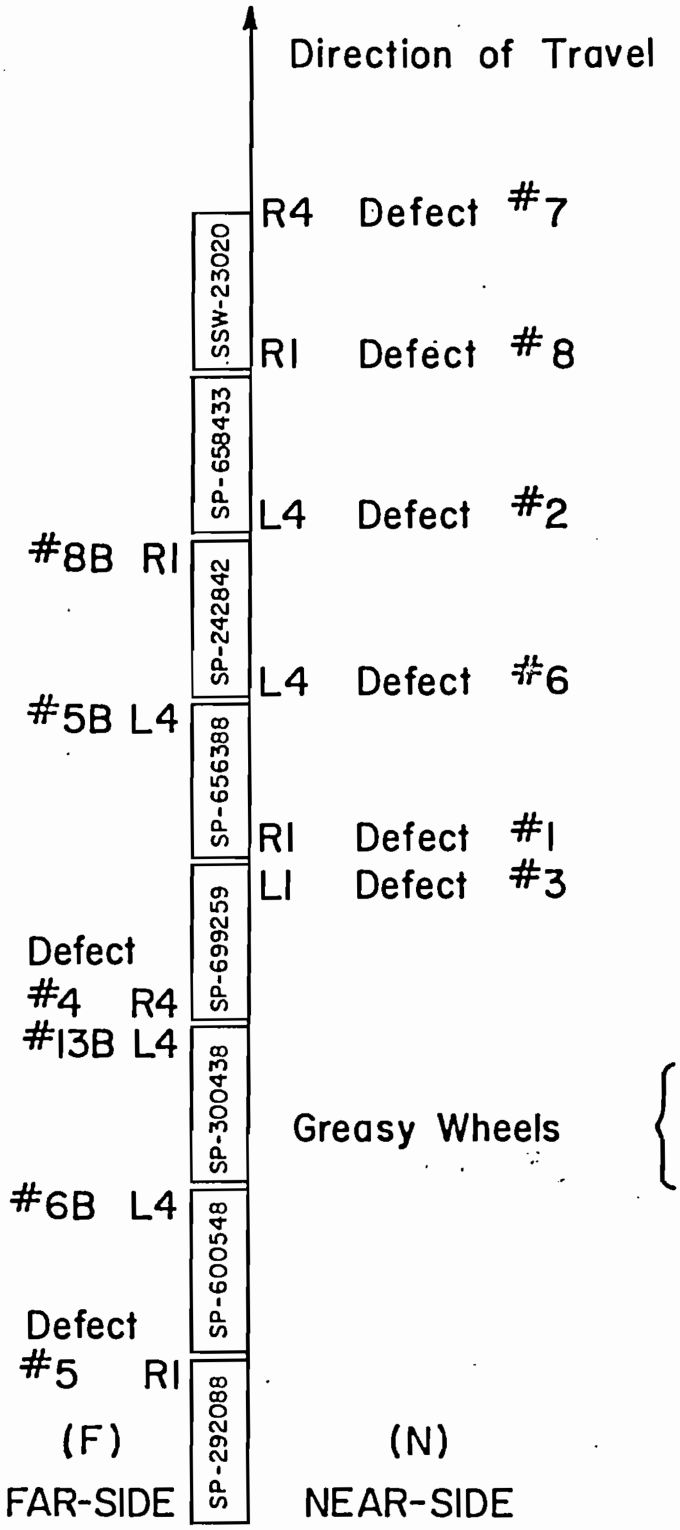
PROSPECTIVE SITES
(MAY 5, 1981)

	1	2	3	4	5	6	7
		GALVESTON		ENGLEWOOD YARD			
REQUIREMENTS	7298 CLINTON	CLINTON DRIVE	BRIDGE 5A	RETARDER YARD	YARD ENTRANCE	DOUBLE MAIN TRACK	HARRISBURG TRACK
SPEED	E (20 mph)	E (15 mph)	E (15mph)	POOR (9 mph)	POOR (9 mph)	POOR (45mph)	E (15 mph)
ELECT. POWER	E	E	E	E	E	E	E
COMMUNICATION	E	E	POOR	E	E	E	F
SECURITY	F	F	F	G	G	F	F
ACCESS BY ROAD	E	E	F	G	G	POOR	E
CONVENIENT FOR TEST CONSIST	F	F	F	E	E	POOR	F
TRAINS/DAY	G (6)	G (6)	G (6)	G (2000car)	G (6)	E (15)	G (6)
MIN.DISTURB.TO RESIDNTAL AREA	E	G	E	E	E	POOR	E
EASE OF INSTAL	E	POOR	G	E	E	POOR	G
FAIR MIX OF CARS	G	G	G	G	G	E	G
LOW SPL DISTRB	G	G	G	G	G	G	G
CONVENIENT TO VALIDATE RESLT	E	E	G	E	E	POOR	POOR
MIN. INTERFER. W/NORML OPER.	E	E	E	E	E	POOR	E
SUITABLE TO SHOW VISITORS	E	E	F	E	E	G	G
STOP & GO REVERSING	F	E	E	POOR	G	E	E

Some sound pressure level measurements were made at the site. The background noise was found to vary from 80 dBC to 83 dBC. With a train passing at 15 mph the level was found to vary from 93 dBC to 98 dBC.

1.10 The Test Consist

A test consist was assembled by the Southern Pacific. Fig.1.10 shows the eight cars of the consist and the location of defective wheels among the 32 axle sets. It should be noted that the cracked wheels were all specimens withdrawn from service. Two wheelsets had cast in defects manufactured by Griffen Wheel specifically for these tests. Three wheelsets were deliberately left in a greasy condition. Further information on the defective wheels is given in Tables 1.2 and 1.3. A preliminary inspection of these wheels was made by project personnel and tape recordings of the sound produced by hammer tapping were made for use in software development.



Axle Number	Defect Description
1	N: Thermal Cracks
2	
3	
4	N: Many Large T.C.'s F: Small T.C.'s
5	
6	
7	
8	N: Inclusion
9	F: Rim Crack
10	
11	
12	N: Multiple T.C.'s
13	F: Rim Crack
14	
15	
16	N: Inclusion
17	N: Plate Crack
18	
19	
20	F: Plate Crack
21	F & N: Flat Spots
22	
23	
24	
25	F: Multiple Thermal Cracks
26	
27	
28	
29	F: Thermal Cracks
30	
31	
32	

FIGURE 1.10
S.P. TEST CONSIST

TABLE 1.2

LIST OF DEFECTIVE WHEELS SUPPLIED BY S. P.

DEFECT NO.	WHEEL S. N.	DESIGN	MFG.	CLASS	DESCRIPTION
1	45628	CH36	GRIFFEN	U	MFG. CAST-IN DEFECT IN THE RIM.
MATE WHEEL	(NUMBER NOT RECORDED)				
2	46309	CH36	GRIFFEN	U	MFG. CAST-IN DEFECT IN THE RIM.
MATE WHEEL	(NUMBER NOT RECORDED)				
3	IDENTIFICATION MARKINGS WORN OFF				PLATE CRACK.
MATE WHEEL	"	"	"	"	
4	IDENTIFICATION MARKINGS WORN OFF				PLATE CRACK.
MATE WHEEL	"	"	"	"	
5	10848	CM33	GRIFFEN	U	THERMAL CRACKS (1" TO 1 1/2" LG) IN CENTER OF TREAD.
MATE WHEEL	16958	CM33	GRIFFEN	U	NO CRACKS.
6	16016	CJ33	GRIFFEN	U	MULTIPLE THERMAL CRACKS ON FRONT EDGE OF TREAD.
MATE WHEEL	16015	CJ33	GRIFFEN	U	NO SERIOUS CRACKS.
7	21294	CJ33	GRIFFEN	U	THERMAL CRACKS ON FRONT FACE OF RIM ON EDGE OF TREAD.
MATE WHEEL	21080	CJ33	GRIFFEN	U	NO CRACKS.
8	67476	CJ33	GRIFFEN	U	MULTIPLE LARGE THERMAL CRACKS ON FRONT EDGE OF TREAD. SMALLER CRACKS ON TREAD.
MATE WHEEL	74438	CJ33	GRIFFEN	U	SMALL CRACKS ON TREAD.

The wheels and the defects which they contain are identified in the Table. The defective wheels were stenciled "DEFECT" and numbered 1 through 8 to correspond with the numbers in the Table. The brackets in the Table indicate axle sets.

TABLE 1.3

LIST OF DEFECTIVE WHEELS SUPPLIED BY U. H.

DEFECT NUMBER	DESCRIPTION
8B	RIM CRACK
5B	RIM CRACK
13B	SMALL FLAT SPOTS
6B	THERMAL CRACKS

2. HARDWARE

2.1 Hammer:

The primary requirements for the hammer are that it should produce a signal of the required duration and frequency content, and should make a complete cycle in less than 170 msec. Prior experience showed that a single impact is adequate to produce the required signal if the peak sound pressure level (SPL) exceeds the background noise by 20 dB. The original hammer was mechanically activated by the wheel's passage. There were several drawbacks with this design. First, the action of the hammer was dependent on train speed. Secondly, the velocity of impact was dependant upon the flange height and thirdly, it cannot be electrically controlled.

The idea of an electrically activated hammer was then considered. An analysis was developed, using an idealized hammer design, to evaluate different types of hammer. Figure 2.1 represents an idealized hammer comprised of an impacting head on a pivot arm set into rotational motion by an impulsive force. A restoring spring is used to reset the hammer.

The dynamics of the hammer are governed by the rotational form of Newton's 2nd Law:

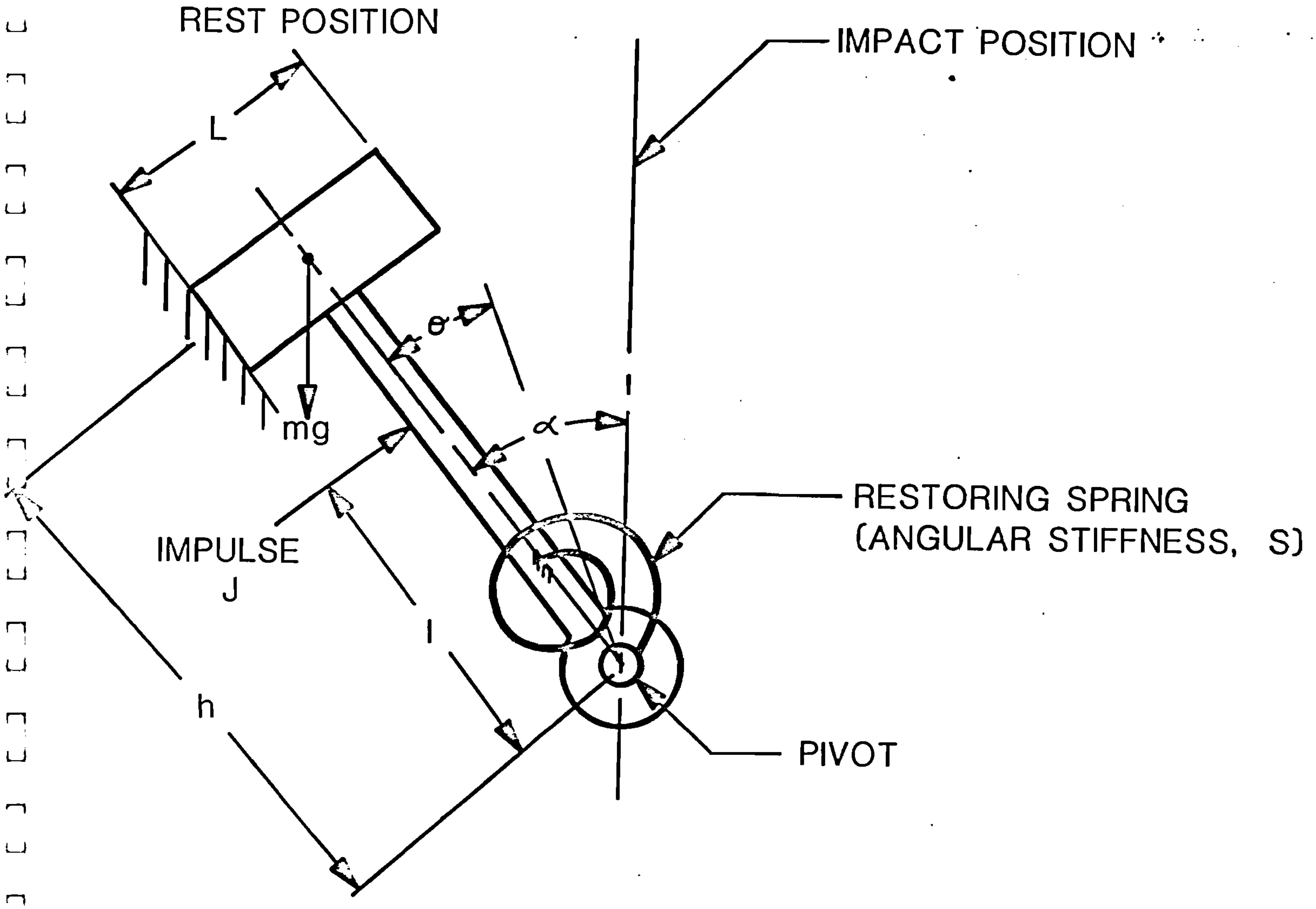


FIGURE 2.1 IDEALIZED HAMMER DESIGN

DWG A900-1011-AW

$$\tau - mgh \operatorname{Sin}(\alpha - \theta) = I\ddot{\theta} + S\theta \qquad (2.1.1)$$

where: τ = applied torgue (or moment)

I = moment of inertia about pivot

S = angular stiffness of spring

m = mass of hammer head

h = length of hammer arm

During the activating impulse,

$$\tau = FL$$

where: L = moment arm of driving force F

and equation (2.1.1) becomes:

$$FL = I\ddot{\theta}$$

Since F varies with time,

$$L\int_0^{T_A} F\,dt = I\int_0^{T_A} \ddot{\theta}\,dt = I\,[\,\dot{\theta}\,]_0^{T_A}$$

$$\therefore \quad LJ = I\dot{\theta}_A \qquad (2.1.2)$$

During the free rotation equation (2.1.1) becomes

$$I\ddot{\theta} + S\theta + mgh \operatorname{Sin}(\alpha - \theta) = 0$$

If α is small and mg is small

$$I \ddot{\theta} = - S\theta$$

Hence,

$$\theta = A \operatorname{Sin} \omega_o t + B \operatorname{Cos} \omega_o t \ ; \ \omega_o^2 = \frac{S}{I} \tag{2.1.2a}$$

$$\dot{\theta} = A\omega_o \operatorname{Cos} \omega_o t - B\omega_o \operatorname{Sin} \omega_o t$$

When $\tau = 0, \ \theta = \theta_A \ ; \ B = 0 \ ; \ A = \frac{\theta_A}{\omega_o}$

and $\dot{\theta} = \dot{\theta}_A \operatorname{Cos} \omega_o t$ (2.1.3)

and $\theta = \frac{\dot{\theta}_A}{\omega_o} \operatorname{Sin} \omega_o t$ (2.1.4)

When

$$\theta = \alpha \ , \ \tau = T_2$$

$$\operatorname{Sin} \omega_o T_2 = \frac{\omega_o \alpha}{\theta_A} \tag{2.1.5}$$

or $T_2 = \frac{1}{\omega_o} \operatorname{Sin}^{-1}[\omega_o \alpha / \dot{\theta}_A]$

and $\dot{\theta} I = \dot{\theta}_A \operatorname{Cos} \omega_o T_2$ (2.1.6)

the velocity of impact is

$$V_I = \dot{\theta}_I h \tag{2.1.7}$$

Hence the momentum at impact

$$M_I = m V_I \tag{2.1.8}$$

Let the rebound velocity be V_R if the coefficient of restitution is e, then

$$V_R = e V_I \tag{2.1.9}$$

and the change in momentum is:

$$\Delta M = m V_I + m V_R = m V_I (1 + e) \qquad (2.1.10)$$

Let the impulse during impact be I, then

$$I = \Delta M = m V_I (1 + e) \qquad (2.1.11)$$

Now if the impulse delivered to the wheel is linearly related to the vibrational displacement and this in turn to the acoustic pressure, p, at a distance, then

$$p \propto M \qquad (2.1.12)$$

and hence,

$$SPL = 20 \log_{10} \Delta M + \text{Constant} \qquad (2.1.13)$$

The form of this relationship was determined by an experiment in which a 2 in. diameter ball bearing was allowed to impact a wheel in a pendulum fashion. Impact and rebound velocities were determined from height measurements. Fig. 2.2 shows results of $\log_{10} \Delta M$ versus SPL. The measured slope is 19.8 and the intercept is 121.7 dBC.

Hence,

$$SPL = 20 \log_{10} \Delta M + 121.7 \qquad (2.1.14)$$

This result can now be used for detailed evaluation of various ways of providing the exciting impulse.

A set of specifications was written and a cam activated hammer was designed and built. The hammer was powered by a motor. A

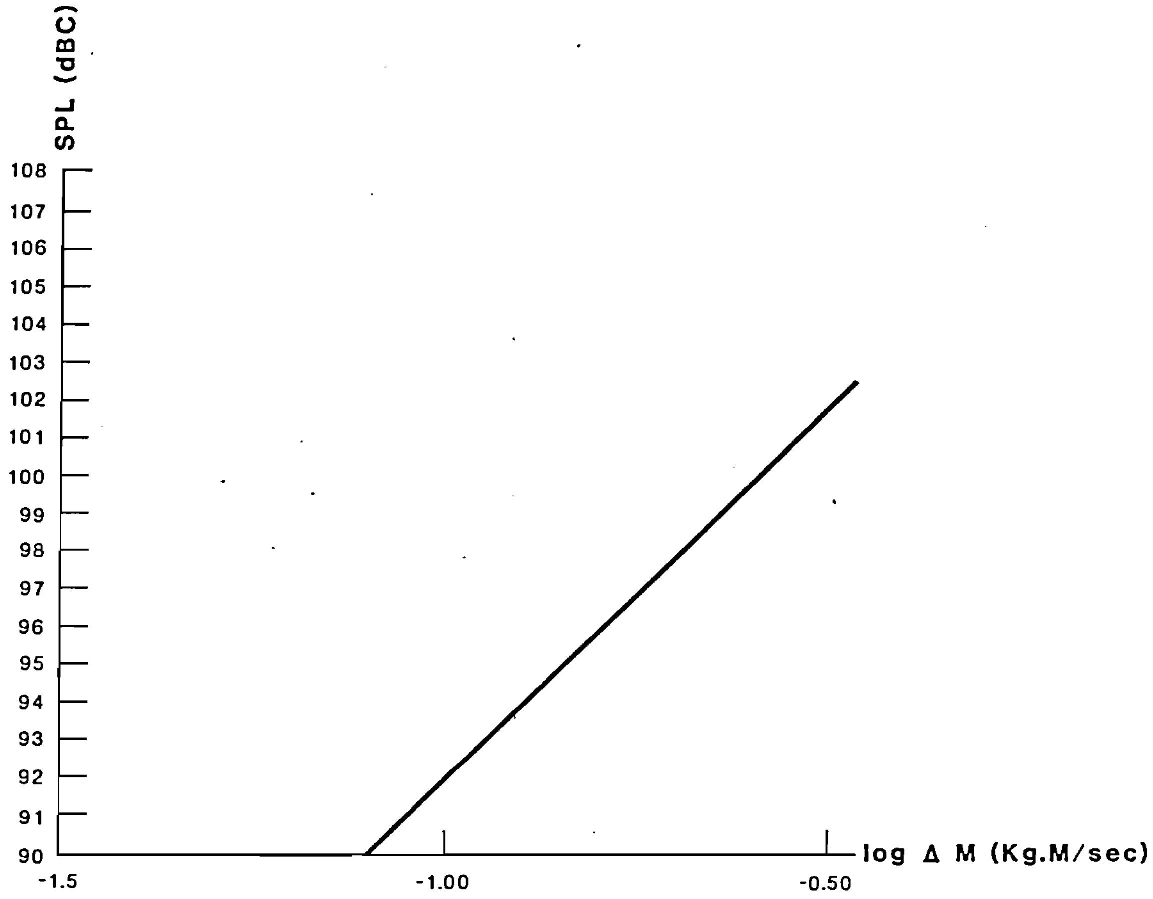


FIGURE 2.2 A PLOT OF SPL VS. $LOG_{10} \Delta M$.

view of this hammer is shown in Fig 2.3. After the hammer was in operation for a while, it was found that the signal obtained was weaker than required, having a signal to noise ratio of only 10 dB. This in turn affected the outcome of the processing performed on the data. To remedy this problem consideration was given to using a stiffer spring and/or the replacement of the hammer head with a heavy ball to get a greater momentum and impact. Other problems encountered were clutch failure, misalignment of the shafts and failure of the links. These problems necessitated modifying the hammers, to keep them in operating condition.

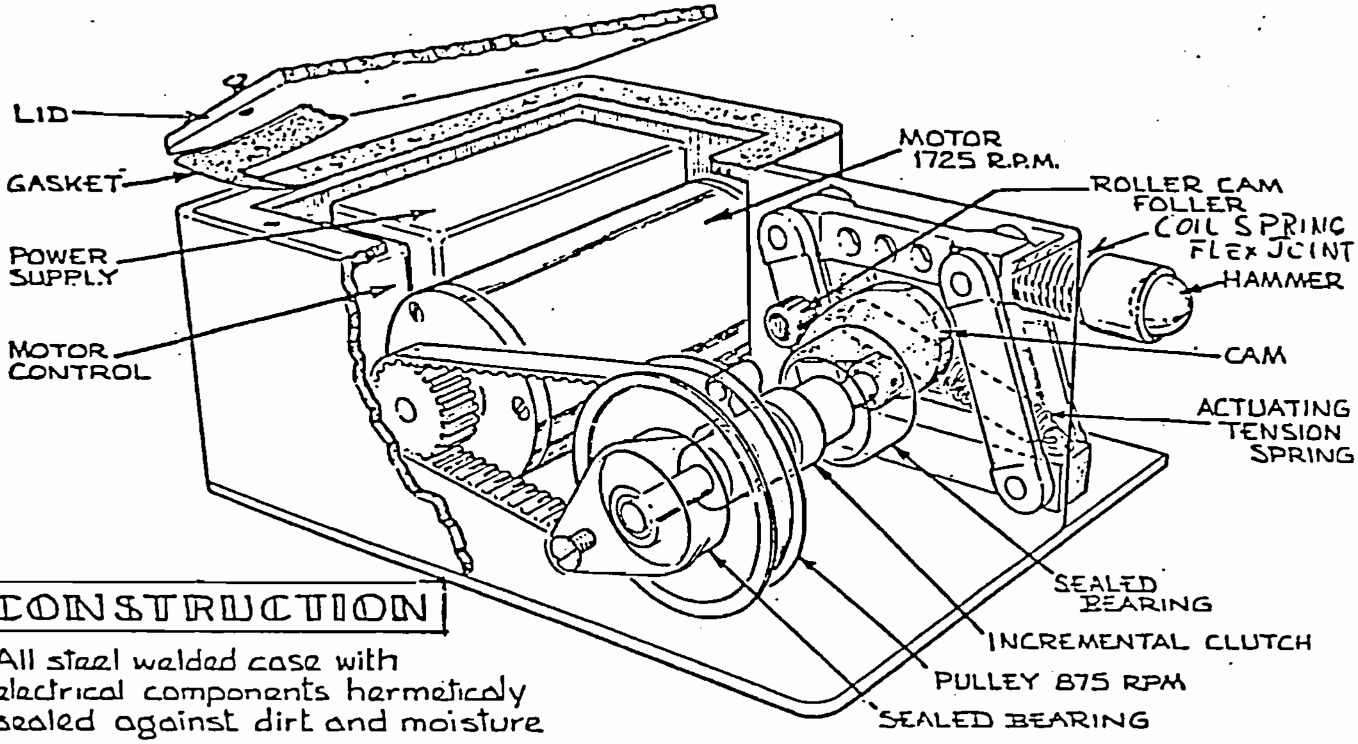
A review of the hammer dynamics was made to find a solution to the problem of low signal to noise ratio. A systematic analysis was made and consideration was given to the momentum of the hammer head, design of the spring, dynamics of the cam and the position of the links. The results confirmed the fact that a stiffer spring and a heavier head was needed in order to get the required sound pressure level. Also, it was found that the necessary torque to drive the hammer needed to be higher, which meant that a fly wheel was required if the same motor was to be used.

A new hammer was designed keeping in mind the drawbacks and the problems encountered with the previous design. One of the primary aims of the new design was to obtain a sound pressure level of 20 dB above the background or train noise. Many

FIGURE 2.3

MOTOR DRIVEN EXCITER

WHEEL CRACK DETECTOR HAMMER
-OPERATES WHEN TRAIN IN MOTION-

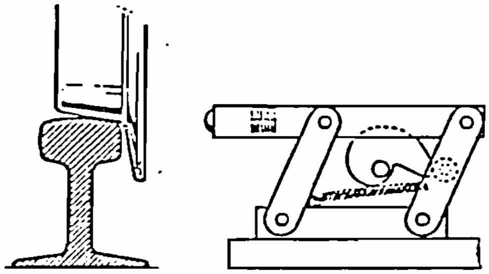


CONSTRUCTION

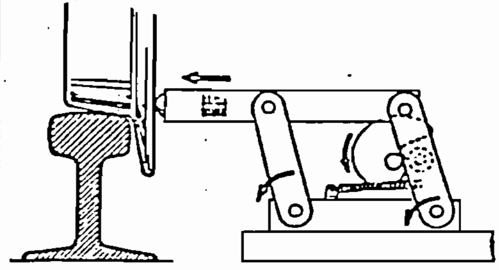
All steel welded case with electrical components hermeticaly sealed against dirt and moisture

OPERATING SPEEDS

Operates with train speeds of 1 mph to 20 mph. Hammer cycle time 80 milliseconds.

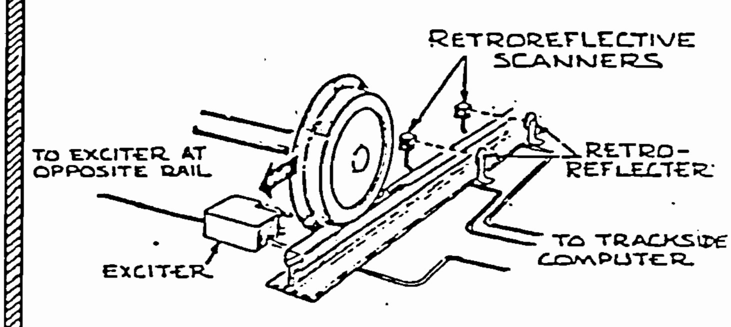


A



B

INSTALLATION



OPERATION

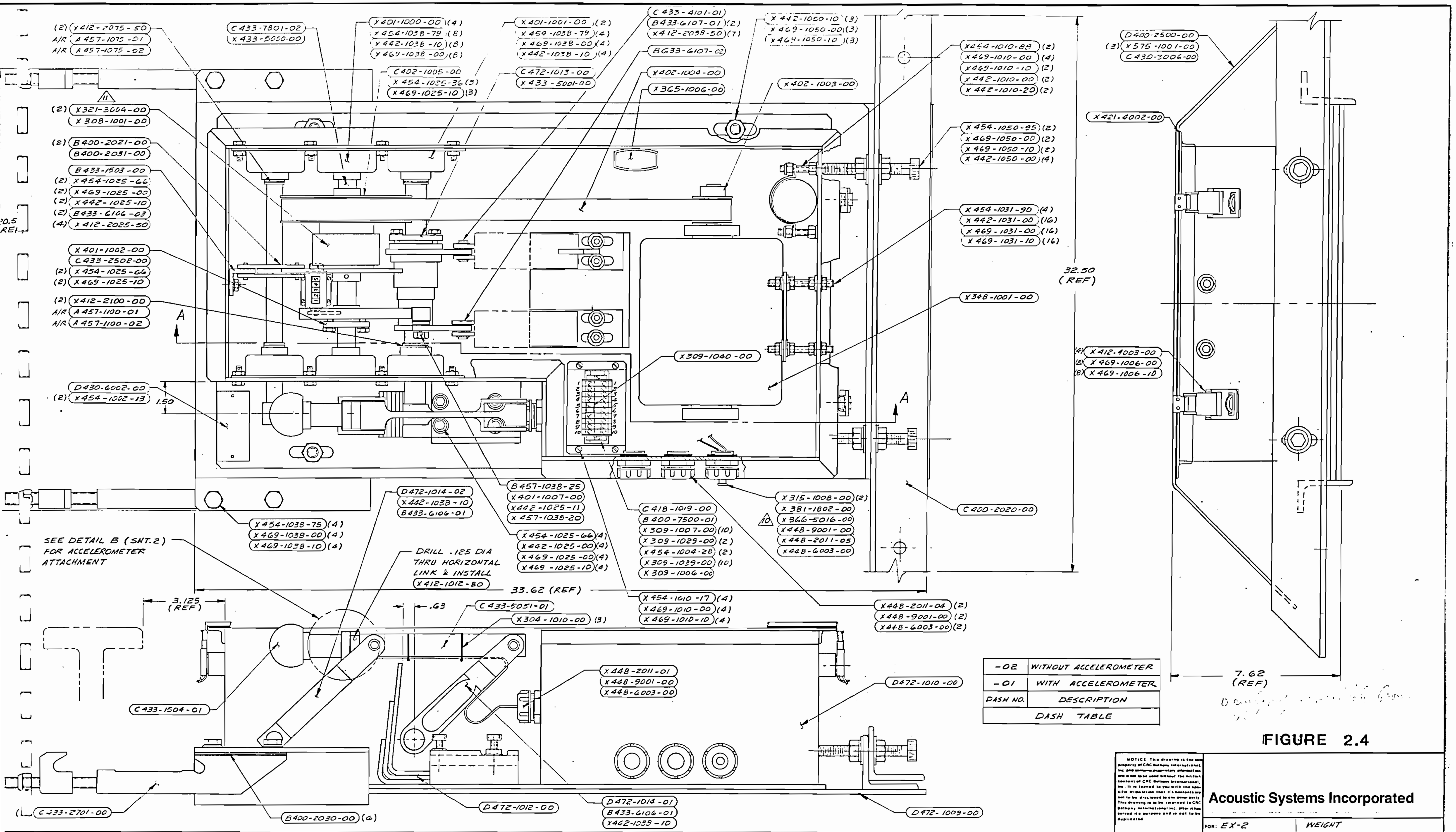
A Unit is cocked and awaiting signal from the trackside computer

B Signal received from computer which energises the clutch solenoid to release the pawl. Shaft and cam then rotates ON revolution counterclockwise, allowing hammer to snap forward-striking the passing wheel. Cam continues to rotate, returning to the cocked position as in A, where it is ag held by the pawl until next signal generated by the following wheel.

additional features have been incorporated in the new design. An assembly drawing of the new hammer is shown in Fig. 2.4. An extensive series of test were performed on the newly designed hammer to correct any problems before it was actually put to use. A brief outline of the tests performed is given below.

The first series of tests were conducted on the hammer components to see if they performed true to the specifications. A few minor problems were encountered during the assembly and starting of the hammer. They were corrected before the actual testing began. The drive springs were tested to determine the spring rate. The results obtained were within 2% of specification. The tests on the cam showed that the clutch was not indexing consisently. This was determined by the position of the cam follower on successive cycles. Also, it was found that the cam follower bounced off the cam surface (instead of rolling). It was concluded that the cam surface was sensitive to indexing and a solution to the problem was to finish the cam surface so that it was perfectly square.

The sound pressure level was determined each time the hammer hit the wheel. It was found that average sound pressure level (SPL) was around 115 dB (C scale). (The SPL meter, B & K type 2203, was held about 6 inches and 6 feet from the wheel). The SPL was also determined for impacts at different points on either side of the load line. The SPL was also measured with two driving springs instead of three. It was found that the SPL with two



-02	WITHOUT ACCELEROMETER
-01	WITH ACCELEROMETER
DASH NO.	DESCRIPTION
DASH TABLE	

FIGURE 2.4

NOTES FOR MECHANICAL DRAWINGS
UNLESS OTHERWISE NOTED
.0 ± .05
.00 ± .02
.000 ± .005
ANGULAR ±
SURFACE FINISH IN MICROINCHES
RMS

LTR.	ZONE	REVISIONS	DR. CHK.	APP.	DATE	LTR.	ZONE	REVISIONS	DR. CHK.	APP.	DATE	NUMBER	REFERENCE DRAWINGS
△	—	RELEASE	HA		JAN 83	△							
△	—	REVISED	HA		1-9-84	△							
△						△							
△						△							
△						△							
△						△							

8 7 6 5 4 3 2 1

DRAWN BY	HA	DATE JAN 83
DESIGNED BY		2-7-83
CHECKED BY		2-9-83
JOB ENGR		2-9-83
PROJ ENGR	SMC	2-9-83
CLIENT		
PRINT ISSUED FOR:		

Acoustic Systems Incorporated

FOR: EX-2 | WEIGHT

ASSEMBLY
AS1- EX-2 EXCITER

SHEET	SCALE	CONTRACT NO.	DRAWING NO	REV
1 OF 2	1/2		D220-1017-00	△

REVISION
ISSUED

springs was only about 1dB less than that obtained with three springs. It was then decided to continue further tests with two springs instead of three. This meant that the loading on the mechanical parts was substantially reduced.

A test for multiple hits showed that the ball bounced off the wheel a second time on a number of occasions. The cause for this was found to be the spring in the hammer head. It was then decided to have a rigid attachment rather that a spring. A tubular rigid connection was then made and after its installation, further tests gave no indication of double impact.

At this point the hammer was tested for repeatability of impact. It was found that the impact was consistently made within about 3 inches from the load line. Also a record of the response time showed consistency. The response time was found to be about 68 ms. The full cycle time was found to be 136 ms.

Finally, the hammer was put through an endurance test. In this test, the hammer was allowed to run continuously till it completed 12,000 impacts at an average rate of one impact per second. Except for a few minor problems, the hammer passed the test successfully. No parts were damaged during the test. Due to the vibrations and the impact force, some parts loosened up. Some of the mountings were corrected accordingly.

2.2 Wheel Sensors:

There is a set of wheel sensors associated with each hammer. These sensors are in front of the hammer and are used to detect the train speed and direction. It is necessary to compute the train speed in order to determine the correct time to activate the hammer. The system is designed so that the wheel is struck when its axle is above the hammer. If the sensors indicate that the train is moving in the wrong direction, the hammer will not activate.

Initially, a set of three optical senors were used with each hammer. Each sensor unit consisted of a scanner and a reflector. The scanners were retro-reflective photoelectric systems consisting of an LED light source, sensor and amplifier in one housing. The sensor is adjusted so that the light beam from the scanner is aimed at the retro-reflective mirror. During the course of operation numerous problems were encountered with this type of sensor. A typical problem was that the sensors required frequent adjustments, without which there were numerous missing pulses. It was felt that the original specifications were not very stringent and experience showed that there were additional requirements that were needed for a sensor to perform well. The new set of sensor specifications is outlined in Appendix 2. Some commercially available sensors, including the optical sensors were rated against these specifications.

A data summary was made on the 3 commercially available sensors, the optical sensor as it was and as it might have been when modified. Table 2.1 summarizes these this data.

Ratings were made by as shown in Table 2.1 scoring each sensor against the specifications as follows:

3= meets specifications,

2= easily modified to meet specifications,

1= modified to meet specifications with difficulty

0= impossible to modify to meet specifications.

A weighting was attached to the specifications for relative importance as indicated, to arrive at final rankings which were:

1.	Siemens Magnetic (Score)	(80)
2.	Siemens Mechanical	(77)
3.	Servopole Magnetic	(66)
4.	Modified Optical	(60)
5.	Existing Optical	(41)

The Siemens magnetic sensor was chosen over the rest based on the rankings. Comparing the Siemen's magnetic wheel detector with the optical sensor, the following points were noted.

1. The former does not miss wheels while the latter does miss wheels. Mounting off the tie would probably help the

TABLE 2.1 DATA SUMMARY

	Servopole Magnetic Wheel Detector	Siemens Magnetic Wheel Detector	Siemens Mechanical Wheel Detector	Existing Optical System	Modification of Optical System
Pulse produced Accuracy and Reliability	GOOD	GOOD	NOT GOOD	NOT GOOD	GOOD
Train speed to Actuate Sensor	5 MPH - UP	0 MPH - 50 MPH	0MPH-100MPH	0MPH-15MPH	0MPH-20MPH
Missing Pulses	NO	NO	NO	YES	NO
Extra Pulses	NO	NO	NO	YES	YES
Compatibility with Existing Electronics	0			GOOD	GOOD
Clearance Requirements	OK	OK	OK	NO	NO
Installation	EASY (1 HOUR)	EASY (30 MIN)	EASY	POOR	FAIR(3HR)
Ruggedness	RUGGED	RUGGED	RUGGED	FAIR	FAIR
Adjustment Internal		EVERY 6 MONTHS	NEED MAINT.	WK.EVEN LESS	MONTHLY
Ease of Adjustment		SIMPLE	SIMPLE	NOT EASY	EASY
Temperature Range	-30 F TO +60 F	-40 F TO 100 F	-40 F-+160 F	GOOD	GOOD
Humidity Range	0 TO 100%	0 TO 100%	0 TO 100%	GOOD	GOOD
Rain and Snow Resistance	GOOD	GOOD	GOOD	DOES EFFECT	FAIR
Effect of Dirt	GOOD	GOOD	GOOD	POOR	GOOD
Delivery	1 MONTH	3 WEEKS	1 MONTH		6 WKS.
Cost	$950.00	$900.00	$500.00		$800.00

TABLE 2.2 RATINGS

		Servopole Magnetic Wheel Detector		Siemens Magnetic Wheel Detector		Siemens Mechanical Wheel Detector		Existing Optical System		Modification of Optical System	
Pulse produced											
Accuracy and Reliability	4	x 2	8	x 2	8	x 2	8	x 1	4	x 3	12
Train speed to Actuate Sensor	3	x 0	0	x 3	9	x 3	9	x 3	9	x 3	9
Missing Pulses	4	x 3	12	x 3	12	x 3	12	x 1	4	x 3	12
Extra Pulses	4	x 3	12	x 3	12	x 3	12	x 1	4	x 1	4
Compatibility with Existing Electronics	2										
Clearance Requirements	1	x 3	3	x 3	3	x 3	3	x 0	0	x 0	0
Installation	1	x 2	2	x 3	3	x 3	3	x 1	1	x 1	1
Ruggedness	1	x 3	3	x 3	3	x 2	2	x 1	1	x 1	1
Adjustment Internal	1	x 2	2	x 3	3	x 1	1	x 1	1	x 2	2
Ease of Adjustment	1										
Temperature Range	1	x 3	3	x 3	3	x 3	3	x 3	3	x 3	3
Humidity Range	1	x 3	3	x 3	3	x 3	3	x 3	3	x 3	3
Rain and Snow Resistance	2	x 3	6	x 3	6	x 3	6	x 1	2	x 2	4
Effect of Dirt	1	x 3	3	x 3	3	x 3	3	x 0	0	x 3	3
Delivery	3	x 3	9	x 3	9	x 3	9	x 3	9	x 2	6
Cost	1										
			66		80		77		41		60

optical sensor.

2. The former does not produce extra pulses while the latter does, and will do so even if remounted.

3. The former passed the most stringent clearance requirements in the U.S.A., while the latter does not, and would not even with remounting because the lightbeam must pass over the rail.

4. Installing the former is quite simple and takes only one man less than 30 minutes, while the latter takes two people more than three hours.

5. The former only needs to be adjusted once every 6 months, while the latter needs to be adjusted almost daily.

6. The former is not affected by rain and snow while the latter is affected by these conditions.

7. The former is not affected by dirt, while the latter is.

The magnetic wheel detecter consists of three major parts: the main magnet, the compensation magnet and the magnetic relay. All magnets are permanent magnets. The flux of the main magnet secures the magnetic relay in its normal position. The compensation magnet has the opposite polarity and shifts the magnetic relay into the reverse position when shunting occurs. It is also used to fuse the magnetic system. The magnetic relay has one independant front and one independant back contact. When a wheel passes the magnetic field of the wheel detector, the wheel flange shunts the main magnet. The compensation magnet forces the magnetic relay to its reverse position. After the wheel has passed, the main magnet returns the relay to its original position.

2.3 Microphone:

The microphone is the transducer which receives the acoustic signals resulting from the use of the hammer on the wheel. It is essential that the signal received at the computer end be as close as possible to that produced by the hammer hit. To meet this end, a list of specifications was drawn, against which prospective choices were compared. The one that best met the requirements was chosen.

The microphone should meet the following specifications:

1. Have a flat frequency response in the range 200-7500Hz, at least.

2. Have a directivity and be located so that its response from a point source of 400 Hz moving in the path of the center of a wheel will be 12 dB down at 5 ft. beyond the excitation point.

sp

3. Meet the clearance reequirements of the Texas Railroad Commission.

4. Be secure from vandalism.

?

5. Require calibration and adjustment at no more than ~~weekly~~ intervals.

6. Be capable of operation in all types of weather likely to be encountered at the site.

Different types of microphones were considered and each rated in accordance with the requirements listed above. The types were dynamic, crystal and electret microphones and hydrophones. Table 2.3 shows the ratings of all the types against the requirements. Although all of them had a good overall rating, the hydrophone was chosen, since it is capable of operation in all types of weather and can withstand more abuse than the others. One drawback, however, is that the hydrophone is vibration sensitive. This was overcome by mounting it on a vibration isolated base. An inexpensive commercial hydrophone was initially used till there arose some doubts regarding its output response. Tests were conducted to determine this output response. The test set up is as shown in Fig 2.5.

The test was carried out in the anechoic chamber at the

TABLE 2.3

MICROPHONES FOR CLOSE-IN LOCATION

	DYNAMIC	ELECTRET	CRYSTAL	HYDROPHONE
FREQUENCY RESPONSE	EXCEL	EXCEL	EXCEL	EXCEL
UNATTRACTIVE TO VANDALS	FAIR	EXCEL	FAIR	EXCEL
CLEARANCE	EXCEL	EXCEL	EXCEL	EXCEL
ALL WEATHER (RAIN, HIMIDITY)	FAIR	GOOD	FAIR	EXCEL
VIBRATION SENSITIVITY	FAIR	FAIR	FAIR	POOR
SENSITIVITY	EXCEL	EXCEL	EXCEL	FAIR
S/N RATIO	EXCEL	EXCEL	EXCEL	GOOD

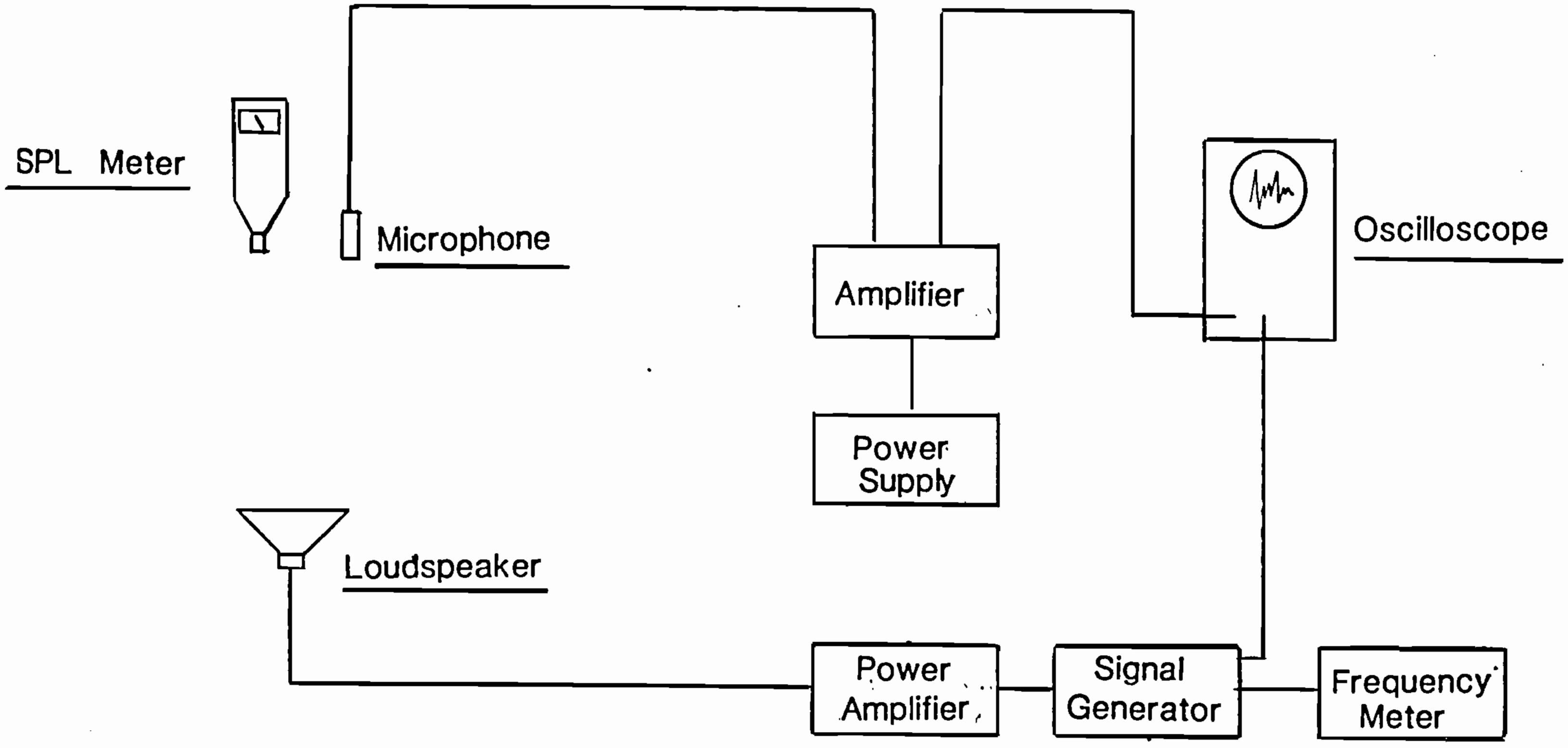


FIGURE 2.5 MICROPHONE TEST SET-UP

A900-1426-AW

University of Houston. A loudspeaker was used to produce the required sound output in the frequency range 400 Hz to 8 kHz. The sound pressure level was maintained at 100 dB(C) throughout. In all the tests, the distance between the microphone and the loudspeaker was 3 ft.

The output response from the various tests showed that the relative voltage variation was drastic as the frequency increased, in comparison with the flat response required for the application.

The hydrophone chosen to upgrade the original choice was the B & K minature hydrophone type 8104. This hydrophone has an excellent set of specifications, the most important being its flat frequency response in the range 0 Hz to 5 kHz. The preamplifier designed by the project team was readily adapted to this hydrophone.

The B & K hydrophone is a piezoelectric transducer i.e., they use piezoelectric ceramics as sensing elements. The piezoelectric sensing element and its internal supporting structure are permanently bonded into a sound transparent polychloroprene-rubber boot. The support body of the hydrophone is made from a 70-30 copper-nickel alloy which has extremely high corrosion resistance to virtually all hostile environments. The internal support, made from brass, is mechanically and electrically isolated from the metal housing, being coupled only by synthetic rubber. This provides vibration isolation of the sensing element. The hydrophone is equipped with an integral cable, the shield of which is connected to the internal support, thus providing electrical shielding for the sensing element. A schematic drawing of the hydrophone construction is shown in Fig 2.6.

2.4 Electronics

The electronics required to interface the computer and the wayside hardware (exciter and sensors) can be considered as three units:

- wayside logic control,
- communications link, and
- signal conditioning and recording unit

The specifications for these units follow from the reasoning of the preceding sections and are set out in Appendix 2. A few notes of explanation are in order. The specification for automatic gain control (4.4) was written in the event the UH mechanical hammer would be used as a back-up. The specifications for a tape recorder interface (6.3 and 6.4) arise from the reporting requirements (see next section). The envelope detectors (6.6) are required to obtain time domain terms.

A block diagram of the wayside logic unit is shown in Appendix 4, and a photograph of the wayside unit is shown in Appendix 5.

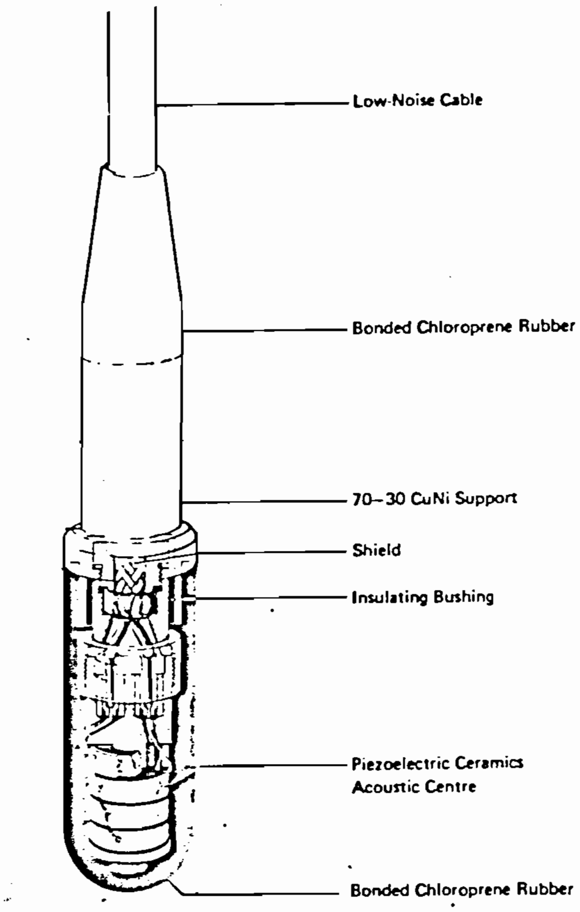


FIG. 2.6 Schematic drawing of hydrophone construction.

A block diagram of the signal conditioning and recording unit is also shown in Appendix 4. A photograph of this unit and the computer hardware is given in Appendix 5.

2.5 Computer Hardware

The computer requirements are the acceptance of the audio data from the excited wheels, pairing the wheel data, analyzing it, determining suspected wheels, saving selected data, generating train reports, and in off-line mode, allowing analysis of data and adjustment of parameters. It includes the following:

1. The basic computer is a Data General S130 Eclipse minicomputer with 128 KB memory, a dual 5 MB disk cartridge in a 50 MB disk unit, two CRTs for the foreground and background consoles, a printer and a hardware floating point arithmetic unit.

2. Two analog-to-digital converter (ADC) channels capable of digitizing data at 22,000 samples/second. The two channels are independently startable. The inputs have a full scale range of ± 5 volts. The sampling clocks are driven by a common source in the Signal Conditioning Unit . The ADC boards are Data General type 4333-A's.

3. One digital input/output (DIO) board is required to accept and generate on/off signals into and from the computer. The input/outputs should be TTL compatible and true (or "on") when low (L). See the DG 4065 + 4066 + 4067 + 4068 documentation for details.

3. SOFTWARE

3.1 General Description

The software has been divided into the following five main areas. (1) Data Acquisition Programs, (2) Train Processing Programs, (3) Utility Programs, (4) Utility Subroutines, and (5) Transform Subroutines. These programs provide a complete system for automatically acquiring waveform data from the wheels of a train passing at the wayside, analyzing the waveforms and reporting on exceptional axles. The individual programs are listed in Table 3.1. Miscellaneous utility programs and the utility subroutine library are listed in Appendix 3.

3.2 DATA ACQUISITION PROGRAMS (ACQ)

3.2.1 WACQ1 - Main Data Collection Program.

This program is executed with one parameter, namely, the name of a data definition file created by the WAGEN program. It initializes its space, tables, files, and the analog-to-digital converters based upon parameters in the data definition file. It then enters an idle loop, checking every second for a train present indication. When the train present signal becomes true, a data file is opened and the analog-to-digital converters are set up to receive waveforms. Under control of the input task,

TABLE 3.1

PROGRAM NOMENCLATURE

1. DATA ACQUISITION PROGRAMS (ACQ)

1.1 WACQ1 - Main Foreground (FG) Data Collection Program.
1.2 WAGEN - Data Definition Program.
1.3 HEADER - Edit Program for Data Headers and Data Definition Files.

2. TRAIN PROCESSING PROGRAMS (PRS)

2.1 CPPROC - Executive Program for Background (BG) Processing.
2.2 PAIR & CARS - Program to Pair Wheels into axles and group axles into cars.
2.3 ANALYZE - Program to Analyze Wheel Pairs and Write Analysis Records for each.
2.4 CLASSIFY - Scans the Analysis records and Flags the Abnormal Axles in the Axle Index.
2.5 PSGRPT - Prints and Files a Train Passage Report Showing the Flagged Axles.
2.6 STORE - Copies the Exceptional and a Sampling of Typical Axles into a "Data-base" File and Frees the Train Data File for Re-use.
2.7 Miscellaneous Processing Programs and Subroutines.

3. UTILITY PROGRAMS (UTL)

3.1 HIST - Produces a Histogram or Scatter Plot from an Analysis File.
3.2 PC - Prints a Consist from the Axle and Car Indexes in a Train File.
3.3 WSPLOT & WSPRINT - Plots or Prints a Time-Windowed Amplitude Spectrogram for Axles in a Train File.
3.4 Miscellaneous Utility Programs and Subroutines.

4. UTILITY SUBROUTINE LIBRARY (LIB)

5. TRANSFORM SUBROUTINE LIBRARY (XLB)

5.1 CFTG - A Discrete, Complex Fast Fourier Transform for Arrays of any Length.
5.2 CFTF - A Discrete, Complex Fast Fourier Transform for Arrays Whose Length is a Power of 2.
5.3 RFTG - For Analyzing a Real Data Array using CFTG.
5.4 RFTF - For Analyzing a Real Array Using CFTF.
5.5 BFLY2 - The "Butterfly" Subroutine Used by CFTF.
5.6 CTPS - Converts a pair of Waveforms to Power Spectra.

and interrupt service routines the analog-to-digital converters are started, independent of one another, by their respective sync-burst-detected interrupts. When the required waveform length has been collected, the ADCs generate another interrupt which causes the input task to add header information into each waveform, including the time it was collected, and pass the waveform buffer along to the disk-writing task. Many buffers are available to the input task so as to prevent loss of data if the disk-writing task gets behind. After the train passage is complete and the train present indication becomes false, the data file is closed and a check is made to see if background processing of the data is called for by the data definition control file. If the background program is check-pointable (i.e., it is not processing a previous train's data), then the current background will be checkpointed and the program CPPROC will be executed in the background to control the processing of the data just collected. The foreground program will then assign the next data file number and wait for the next train.

3.2.2. WAGEN - Program to Define Data Collection

This program builds a data definition command file from information acquired from the operator. This information includes the numbers to be used, the maximum number of output files and their type, the maximum number of waveforms, the template to be used in construction data file names, the next output file number and next train number, a two-character code indicating the source of the data, the initial value for the digital output control word, the ADC clock source, a seventy-two-character remark to go into the data files, the sampling frequency, the sensitivities of the sensors, the distance between the near and far side sensors, and a file name for automatic processing of the train data by the background, if any.

3.2.3 HEADER - Edit Program for Data Header and Definition Files

This program allows changes to be made in the data definition file and train data header files. These changes are controlled so as not to destroy the data or its integrity. This program is especially useful for changing comments and remarks that go into the data files.

3.3 Train Processing Programs (PRS)

3.3.1 CPPROC - Executive program for Background (BG) Processing.

This background program is executed by the foregound after the foregound checkpoints a previous background program. This program takes the place of the Command Line Interpreter (CLI). It reads a command file and calls the other background programs in the sequence specified by the command file. The programs called by this program must be set up as specified in the header of CLI.FR . The program CLI writes a log file, and if errors are discovered, it takes the appropriate abort action. At the end of the command file, the checkpoint background program is resumed.

3.3.2 PAIR & CCARS - Pair Wheels into Axles and Group Axles into Cars.

The program PAIR reads in the wheel-passing times from both the near and far side waveform headers. A search of possible near side-far side pairings is carried out until a list of the best possible wheels pairs is determined. Then if some wheels still remain unpaired, the table is rescanned, converting times to distances in an attempt to pair the remaining wheels.

The program CCARS reads the distances between axles from the axle table produced by the PAIR program and attempts to group these axles into cars, using a "syntactical" pattern recognition method. It presently includes the ability to recognize two-bogy/three-axle-per-bogy cars and two-bogy/two-axle-per-bogy cars. After the best car pairing is determined, a car index is written to the train data file.

3.3.3 ANALYZE - Analyzes Wheel Pairs.

This program makes a first pass through the train data file to determine the average waveform amplitudes. A Fourier transform of the average waveform is computed in order to determine the overall frequency response from the wayside. Then the program scans the waveforms from the wheel pairs again, looking at a narrow time window within each waveform. For each of these windows, the RMS amplitudes are computed and then the spectra um for each is computed. For the greasy wheel calculations, a centroid of the peaks is computed. For the spectral line frequency comparison, the spectral frequencies of the peaks are computed using an interpolation technique. Finally, the common peaks are computed, using the same technique as was used at TTC. The results of the analysis for each pair of wheels is written to an output file with name made up of a T followed by the train number and "AN". This file is available to the classify program.

Variations of this basic analysis program include codes for doing things such as fitting the spectral lines to a wheel vibration mode.

3.3.4. CLASSIFY - Scan Analysis Records

This program reads a train's analysis file, determines the classification of each axle, and writes the classification flags back into the axle record of the train data file. The classification groups include unclassified, good, greasy, uneven wear, defect, and other flags. For those classifications for which a wheel is to be indicated, a symbol "N","F","B", or "?" will be used to designate the wheel. The codes for these classifications must all be coordinated with the passage report program, PSGRPT. Initially, the classifications were based upon picking out extrema in the features from the analysis file and flagging these with some extra symbols, "A" - "G ". Then as the formulas were developed the program codes for classifying greasy wheels and wheels with possible defects were added.

3.3.5. PSGRPT - Program to Print Passage Report

For each train passage, this program reads the train data file and prints a header followed by a detail of each exceptional axle. The header includes the train number, date, and start of passage time. The records on the exceptional axles include the axle number, the car and axle of the car, the side of the defect, the suspected defect or flags, and space for the later insertion of remarks such as car type, car number, car orientation, the observed defect, and other remarks. A trailer gives the number of axle and number of cars, the passage time, the average speed, and the number of axles in each classification.

3.3.6. STORE - Program to Copy Wheel and Axle Data to a Data Base File.

This program is for storing all of the exceptional axle data and some of the typical axle data into a data base file. Special switches, used when calling up the store program, will allow the creation of a new data base (after verification with the operator) and the deletion the train data file so that it can be reused. When a train's data ~~is~~ are entered into the data base, previous records with the same train number will be deleted. For each record in the data base, this directory includes the train number and axle number. The headers on each waveform are updated so that they include the axle classification, car number and axle of car, car type, velocity, distance from the head of the train, sensitivity of the audio channel, and the sampling frequency. The typical axle data are selected so that at any time the base data, contains a selection of axles uniform over time since it was created.

3.4 Utility Programs (UTL)

This directory includes programs of a rather general nature for analyzing and manipulating train data files as well as other files.

3.4.1. HIST - Produces a Histogram or Scatterplot.

This program can analyze the variable fields in a file of one-line formatted records. The file header must include the field definitions. The variables may be analyzed into histogram bands or in pairs in scatterplot format. The format of the data records may pre~~ceed~~ cede the data in the same file or may be in a separate file. The layout of the format definition is specified in the begining of the HIST program.

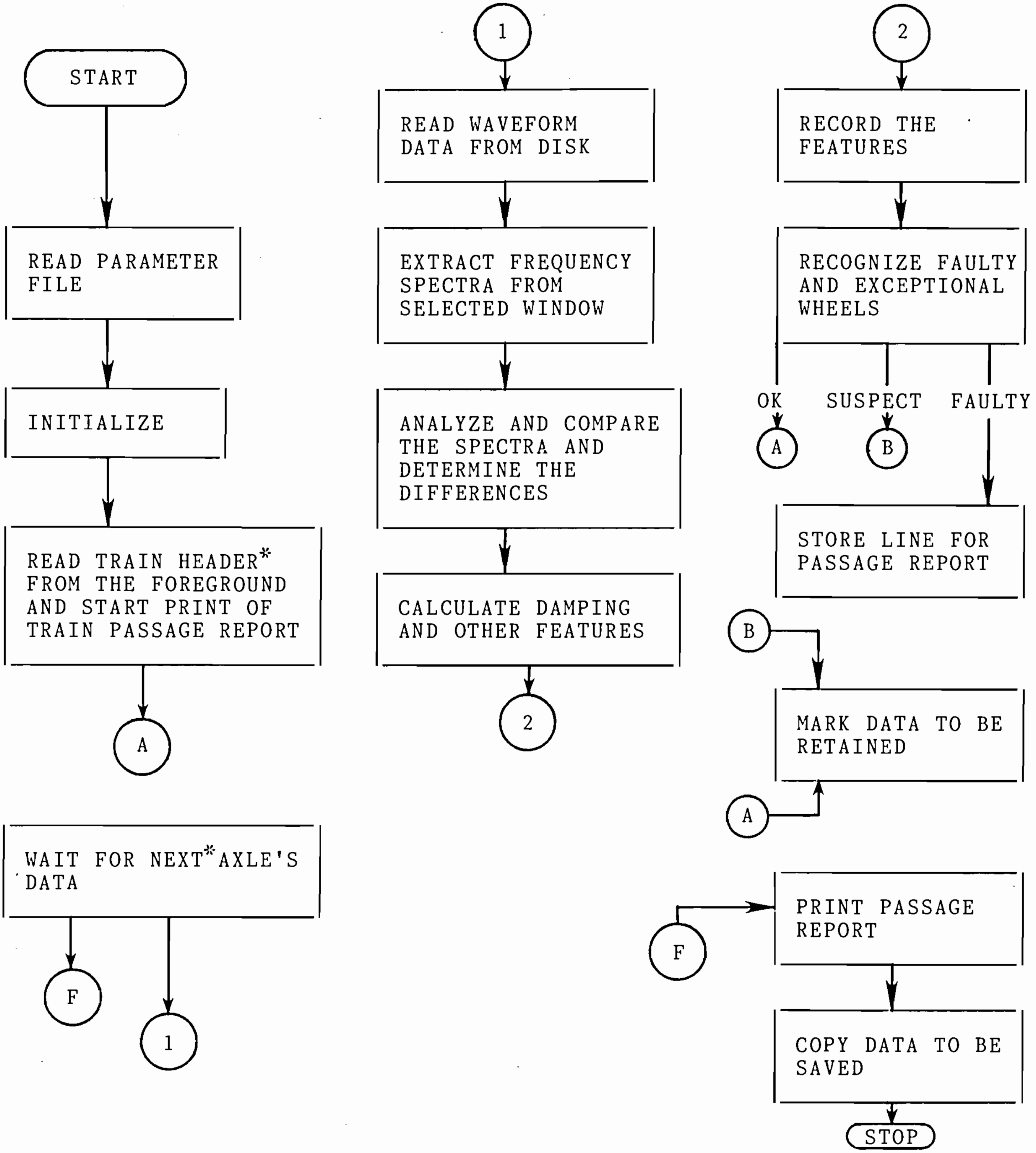
3.4.2. PC - Prints Train "Consist."

This program reads the axle and car indexes in a train file and produces a consist in axle order indicating the car type and classification flags.

3.4.3. WSPLOT & WSPRINT - Plot or print amplitude spectrograms of wheel sounds from a train file.

These two programs will plot on a calcomp plotter or print on a line printer, spectrograms from narrow time windows in the wheel sound waveforms. The data to be plotted may be specified as a range of waveforms, axles, or car numbers.

BACKGROUND DATA PROCESSING PROGRAM (SINGLE TASK, FORTRAN)



* When this program is started be operator, rather than by the data acquisition (FG) program, then the data for just one selected axle will be processed from a disk file instead of from the foreground.

FOREGROUND DATA ACQUISITION PROGRAM (MULTI TASK, ASSEMBLY LANGUAGE)

INTERRUPT PROCESSOR

DISCRETE AND ANALOG I/O

DATA FILES ON DISK

COMMUNICATION TO BACKGROUND

LEFT AND RIGHT WAVEFORM INPUT TASKS

1. GET EMPTY BUFFER
2. ENABLE EXTERNAL DETECTOR
3. WAIT FOR START OF WAVEFORM
4. START ADC
5. WAIT FOR COMPLETION
6. ENQUE WAVEFORM BUFFER TO PAIRING PAIRING TASK
7. GO BACK TO #1.

QUEUES

1. EMPTY BUFFERS AND MESSAGES
2. MESSAGES TO STORE - WAVEFORM TASK
3. MESSAGES TO PAIRING TASK.

CLOCK TASKS

1. MAINTAIN TIME
2. DETECT NO MORE INPUT

BG SERVER TASK

1. COPY AXLE DATA TO WINDOW FOR BG PROGRAM

INITIALIZATION TASK

1. READ PARAMETERS
2. SET UP QUEUES
3. OPEN CHANNELS
4. START TASKS

TASK TO PAIR WHEELS

1. SET COMPUTER READY SIGNAL
2. WAIT FOR WAVEFORM DATA
3. ENQUE WAVEFORM FOR WRITING
4. IF FIRST, START TRAIN TABLE CALL IN BACK GND PGM
5. UPDATE WHEEL PAIRING TABLE
6. UPDATE AXLE TABLE
7. IF END OF TRAIN GO TO #10
8. RELEASE BUFFER
9. GO TO #2
10. GET COMPUTER NOT READY SIGNAL
11. FINISH AND RECORD TABLES
12. WAIT FOR GACK GND TO FINISH WITH TRAIN DATA, THEN GO TO #1.

TASK TO WRITE WAVEFORMS

1. OPEN FILE
2. WAIT FOR WAVEFORM. IF END GO TO #4
3. WRITE TO DISK. GOTO 2
4. CLOSE FILE. TELL BG.

4. SYSTEM PERFORMANCE

The objective of the project was to obtain some preliminary data and to get into a position where, a defective wheel could be found if it were to pass the site. An evaluation of the performance of the system can be obtained from the follow-up made on the train passages, and also from the performance of new algorithms on the data base.

The data base was organized for development of new classification schemes which will enhance the performance of the system in terms of a higher detection rate and lower false alarm rate. Included in the data base are:

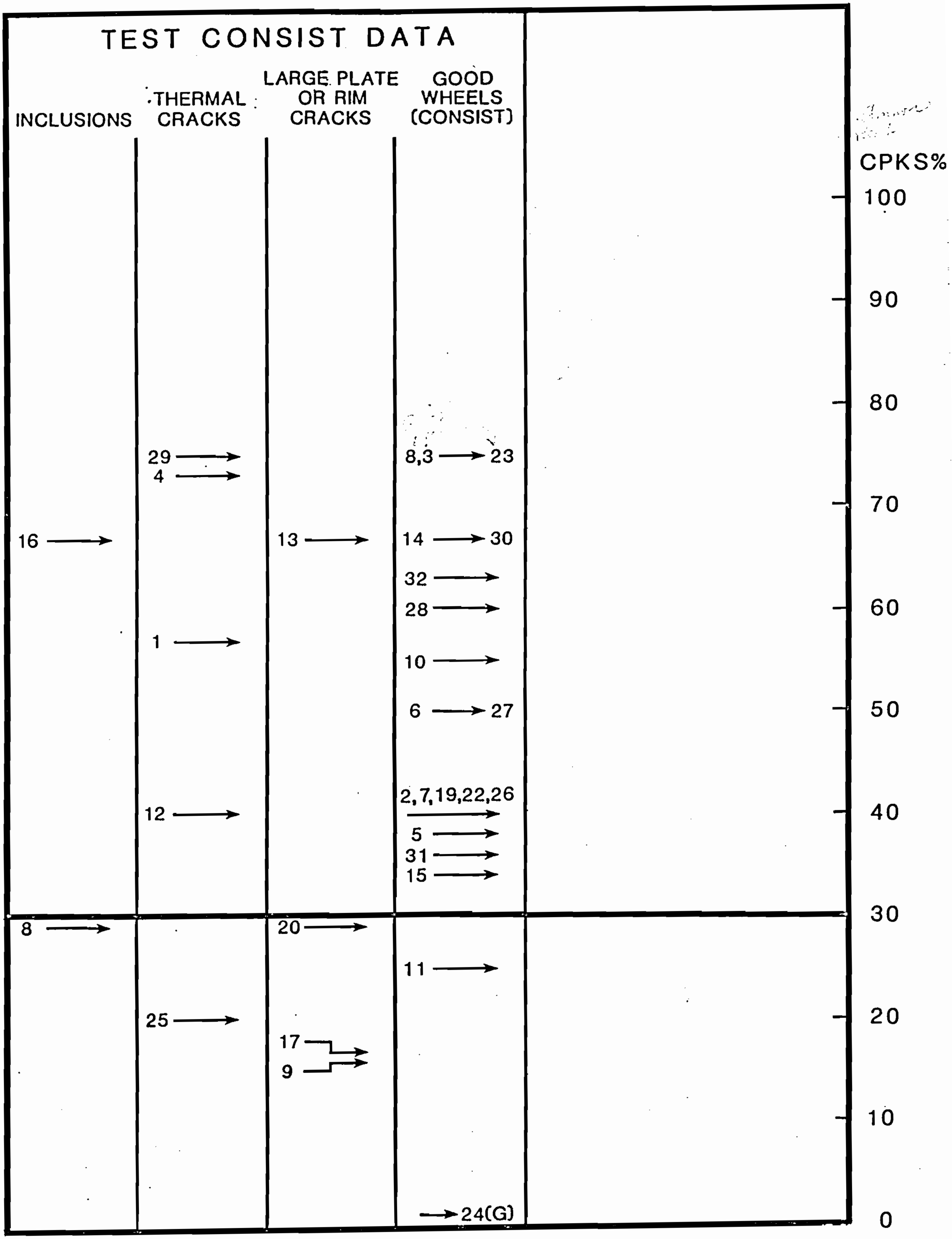
a) digitized signals from the tape recordings of the test consist wheels in the yard;
b) the products of analysis and results obtained for all wheel sets in a);
c) results from the period of utilization of the test consist at the wayside, including digitized signals and products of analysis; and
d) digitized signals from several train passages together with the results and products of analysis.

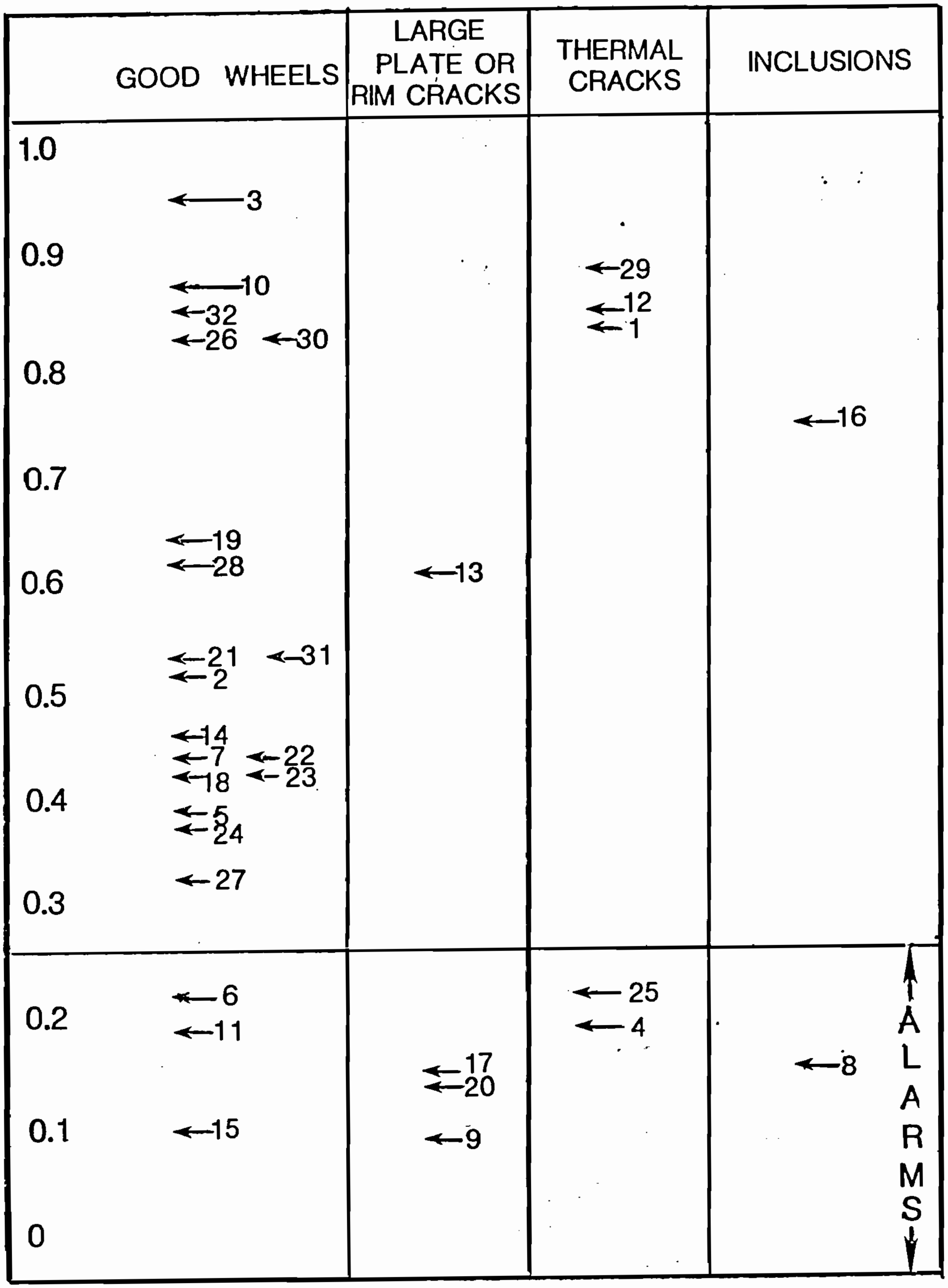
The most important measures of performance are the two system parameters - detection rate and false alarm rate. These two parameters will also serve as the basis in the evaluation of new algorithms. The various indicators that are presently being used to determine the detection rate and the false alarm rate are: spectral cross correlation, common resonances and difference in the amplitude of the signals. A new algorithm, based on the modal frequencies, has given very good results when tested with the yard data. Details of this algorithim is given later in this chapter.

The system performance evaluation was carried out in two parts: the first part was the evaluation of the data base of the consist runs including the data obtained in the yard and the second part involved the evaluation of the data base of the revenue service trains. The results in these cases gave an idea of the detection and false alarm rates that could be obtained with different values of the variables, such as the threshold, delay and frequency weighting which influence the results to a great extent. The initial evaluation was performed on the consist data obtained in the yard. The data was processed using the existing software. The most useful indicators were the percentage of common peaks and spectral cross correlation. A histogram of these variables was plotted as shown in Figs. 4.1 and 4.2. From these figures, it can be seen that the percentage of common peaks by itself gave a reasonably good result. Namely, a detection rate of five bad axles out of eleven and a false alarm rate of two out of seven. A somewhat similar result was obtained with the spectral cross correlation.

TEST CONSIST-YARD DATA

FIGURE 4.1





S.P. CONSIST: SPECTRAL CROSS
CORRELATION: 65 ms DELAY
DETECTION RATE: 6/11
FALSE ALARM RATE: 3/9

FIGURE 4.2 TEST CONSIST-YARD DATA

At this stage, a new algorithim was developed for the classification of wheels based on modal frequencies. It was initially tested on the yard data before incorporating it into the system software. The following is an outline of the procedure and the results obtained using this algorithm.

Signals obtained from a recording made from the test consist on a cassette tape were processed at the computer center. The resonant frequencies were obtained for all the wheels on the consist, using the software described in the preceeding chapter.

The aim was to see whether the frequency values followed a pattern, which would help in separating the good and the bad axles (axles containing at least one bad wheel) and to recognize a bad one if it did exist. First, the frequency values were compared with known theoretical and experimental values to establish any similarities (or dissimilarities). For many of the wheels, it was noticed that the frequency corresponding to the fundamental (400 Hz to 500 Hz) was absent. Secondly, there seemed to be a number of resonances other than the prominent ones in most of the wheel spectra.

The prominent frequencies for the wheels were plotted and the resulting curves for wheels on the same axle were compared. It was observed, that in many of the cases, the curves of both the wheels were either sloping up or down and were quite close to each other. In other cases, the curves were sloping in opposite directions and were widely separated. The latter was observed to be the case for many of the bad axles and a few good ones. After these observations, it was decided that a least squares fit for the set of values for each wheel would give a better picture of the behavior of the numbers.

The procedure used was as follows:

1. The prominent resonant frequency in each interval of 1000 Hz was taken i.e. in the intervals 0 - 1 kHz, 1 - 2 kHz etc. then, the frequency in the 0 - 1kHz range would correspond to the fundamental i.e. mode 2, the one in the 1 - 2 kHz range would correspond to mode 3 and so on. This procedure of picking the prominent resonances was followed because, it was observed in the theoretical results that the frequencies did lie in the ranges as given above, for each mode.
2. The ratio to the fundamental was calculated for each of the frequencies. In the cases where the fundamental did not exist, one was introduced, to avoid any discrepancies at a later stage. The theoretical value of the fundamental was used.
3. The equation, corresponding to the least squares criterion, was deterimined for each wheel. The frequency ratio was taken as the dependant variable and the mode number was the independant variable.
4. The least squares fit is the best fit for the given set of

data in this case. For each of the wheels, the sum of the squares of the deviation of the actual values from this fit was obtained.

5. Having obtained such a number, say S , for each wheel, the difference in the S value for each wheel set was obtained, giving the discriminating number, DN, for each axle.

6. The DN value was plotted for all the axles, and it was observed that the lower DN values corresponded to the good axles for the most part. Futher, the DN for each axle was plotted against the spectral cross correlation as in Fig.4.3 and against the % common peaks number as in Fig.4.4. These plots showed a clearer picture. The good and the bad ones could be demarcated easily. The detection rate from Fig.4.3 is 9 out of 11 with a false alarm rate of 2 out of 11. And from Fig. 4.4, the detection rate is 10 out of 11 with a false alarm rate of 3 out of 13.

The next step was to evaluate an actual consist passage at the site. Several runs were made and the best of these was processed in a manner similar to that of the yard data. The results were not very encouraging. Although the percentage common peaks indicator gave a fair result, the spectral cross correlation and the modal frequency analysis did not perform well on the data. This was due to the fact that the signals obtained from the consist passage contained a high level of noise which meant a low signal to noise ratio. Fig. 4.5 and 4.6 show a spectral plot of the signals obtained for one particular

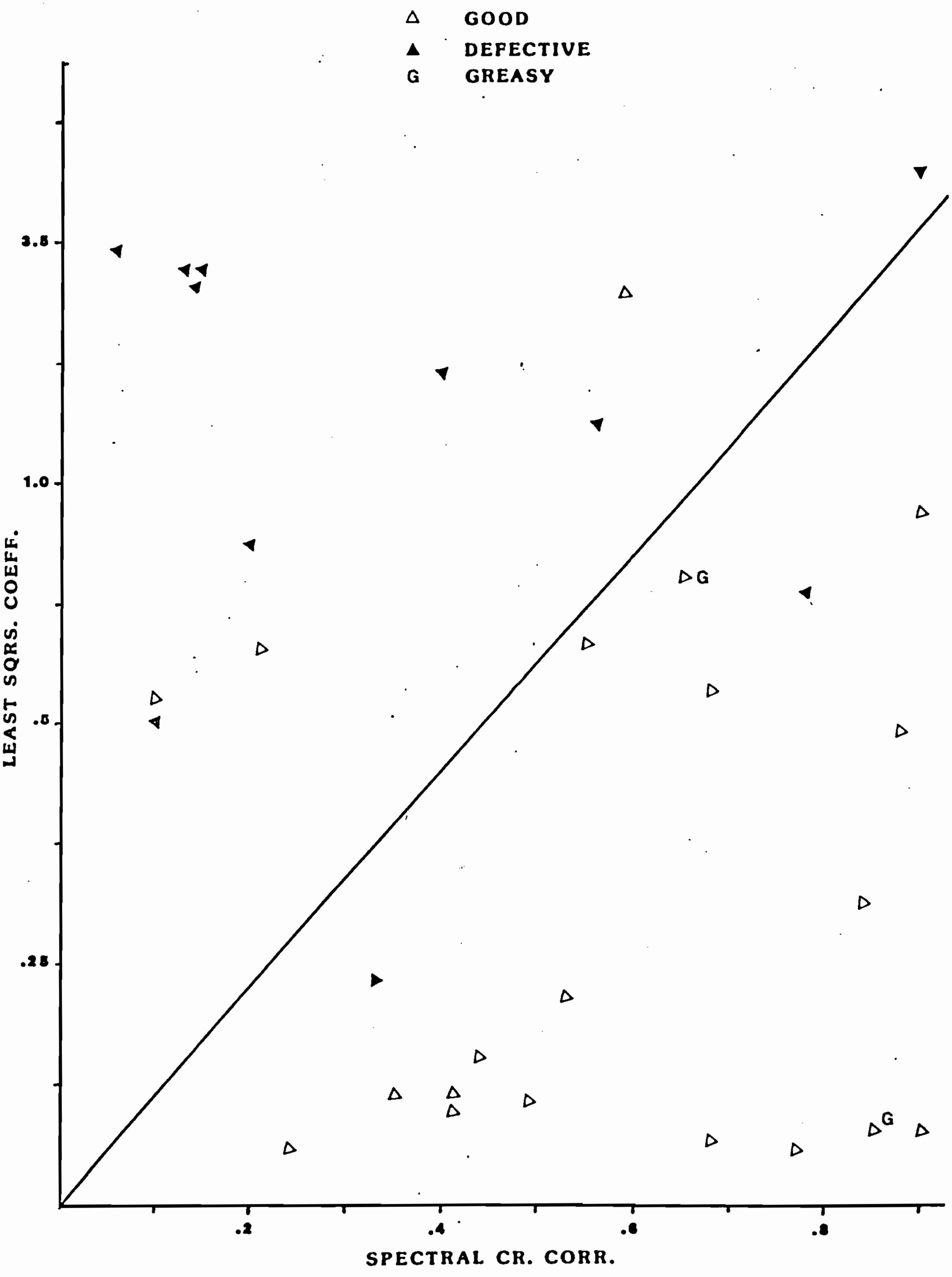


FIGURE 4.3 PLOT OF LEAST SQUARES COEFFICIENT VS. SPECTRAL CROSS CORRELATION

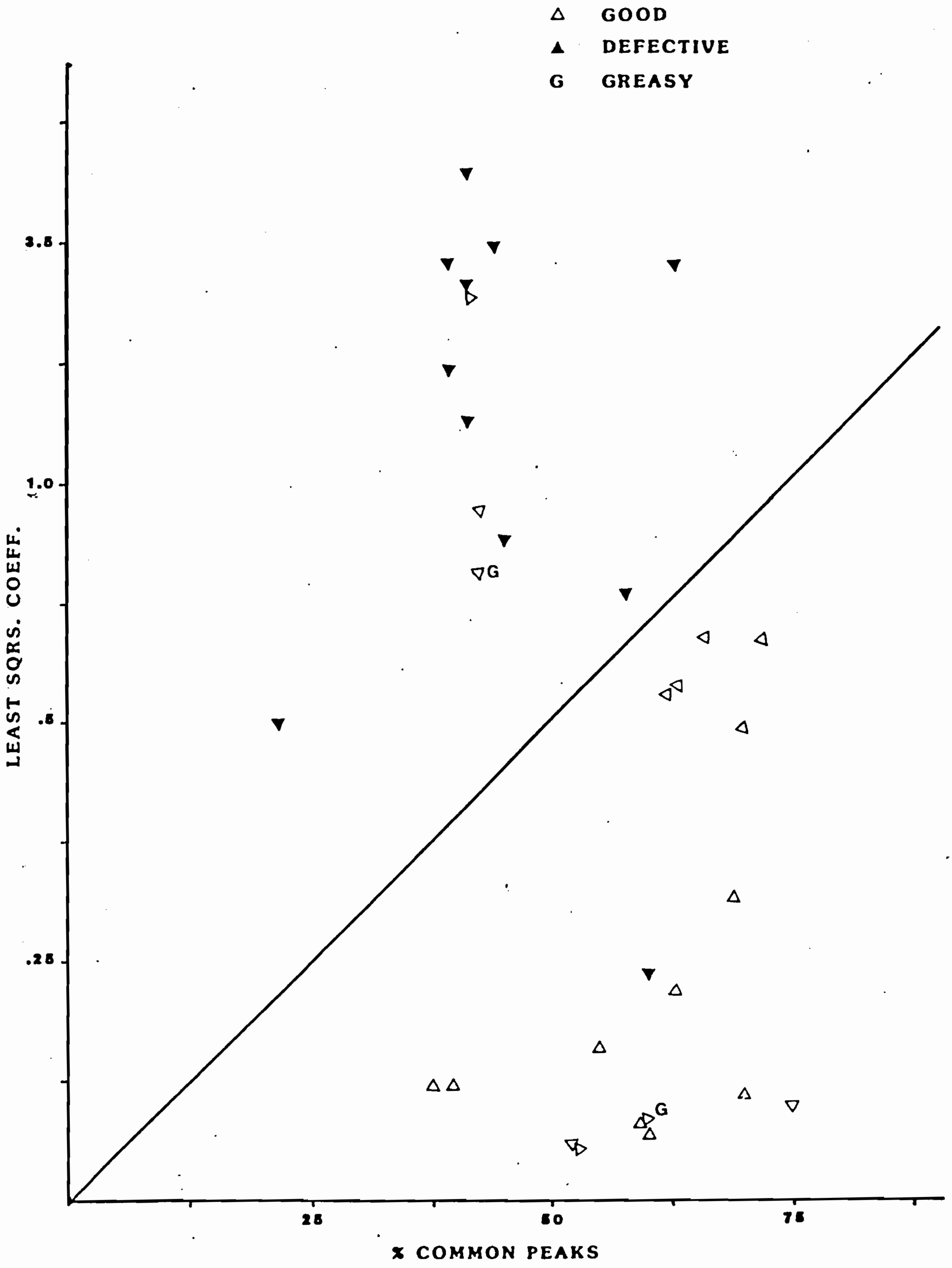


FIGURE 4.4 PLOT OF LEAST SQUARES COEFFICIENT VS. PERCENTAGE COMMON PEAKS

axle from the consist passage and from the yard respectively. The presence of noise is quite evident in the signals obtained from the consist passage when compared with the other plot. A similar observation was made from the plots obtained from a Calcomp plotter. Fig. 4.6a and b show plots of the signals obtained from the consist in the yard for some of the axles. Fig 4.5a shows plots obtained from a consist passage. The presence of noise in the lower frequencies is very evident from Fig 4.5a. The studies made on the consist data yielded some important information regarding the optimum settings for the threshold and delay and also on the effect of frequency weighting.

?

Data from revenue service trains was collected whenever possible. Follow-ups were made on several occasions with encouraging results. On the occasions when a follow-up was made, the following was the condition of the wheels flagged:

Number of Wheels	Condition
4	Grooved tread
3	Flat-spots
4	Shelled tread
7	No visible defect

None of these wheels was condemnable, but on the other hand , some visible defects were found. Fig 4.7 shows the spectral

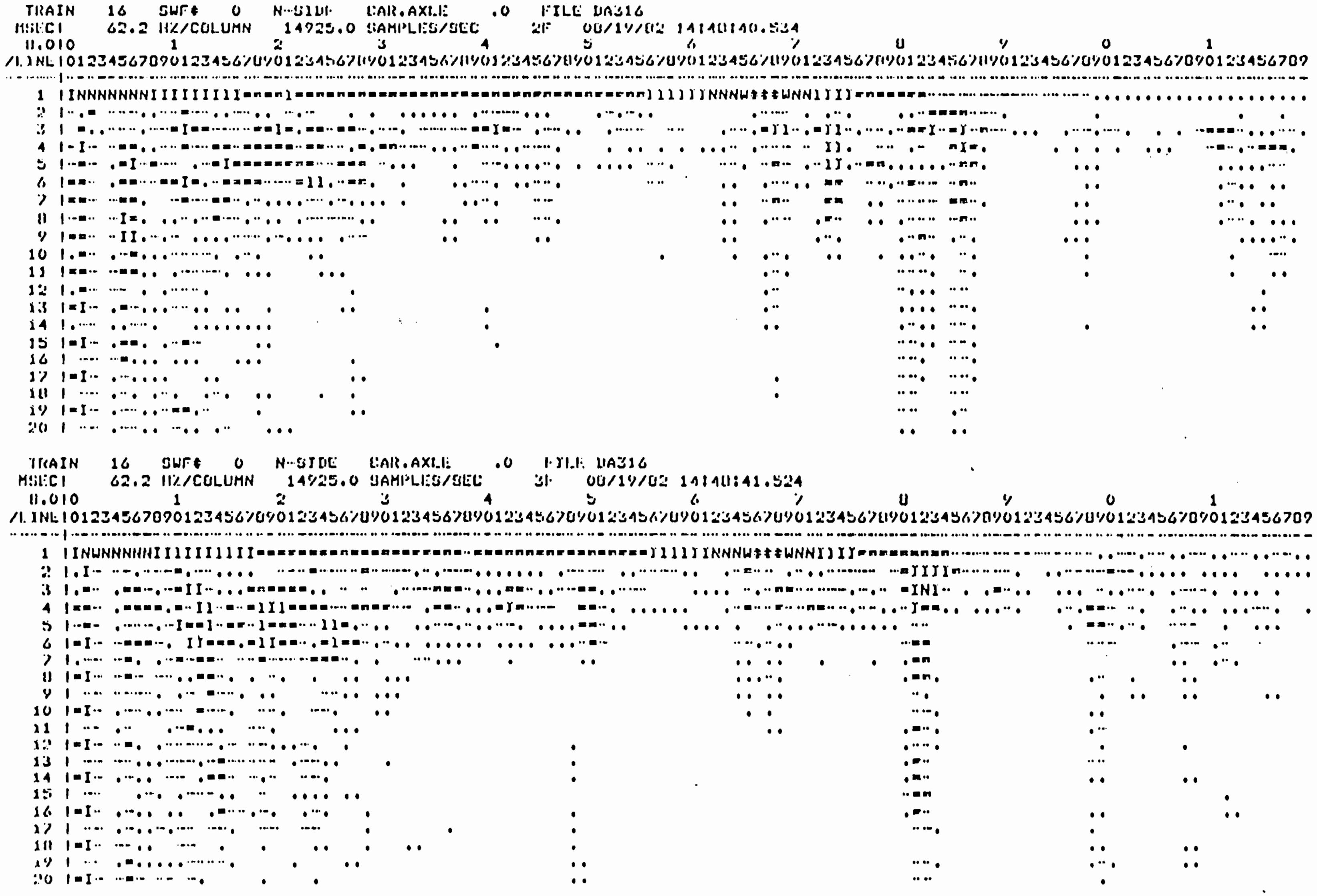


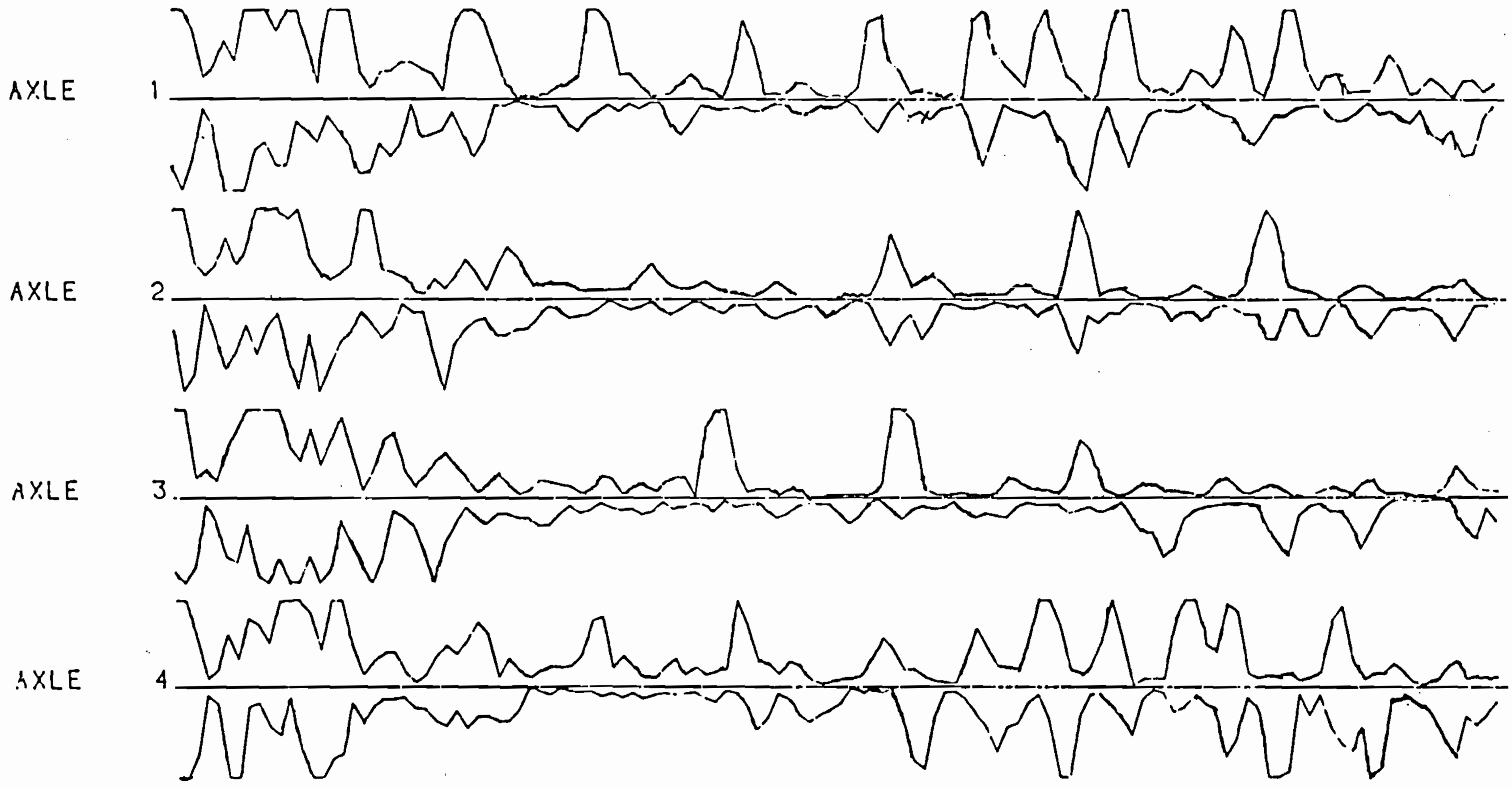
FIGURE 4.5 SPECTRA OF TWO SIGNALS FROM CONSTANT PASSAGE

FIGURE 4.5a PLOTS OF SIGNALS OBTAINED FROM THE CONSIST PASSAGE

TRAIN NO. 16-HT-WS FILE: CA316

REF. SIG. LEVELS (VRMS): 1.0000NS. .4000FS. 14925.0 SAMPLES/SECOND.

PLOT INFO: 128 FREQUENCY BINS. VER = .50 * (AMPL / THRES) ** 1.00.



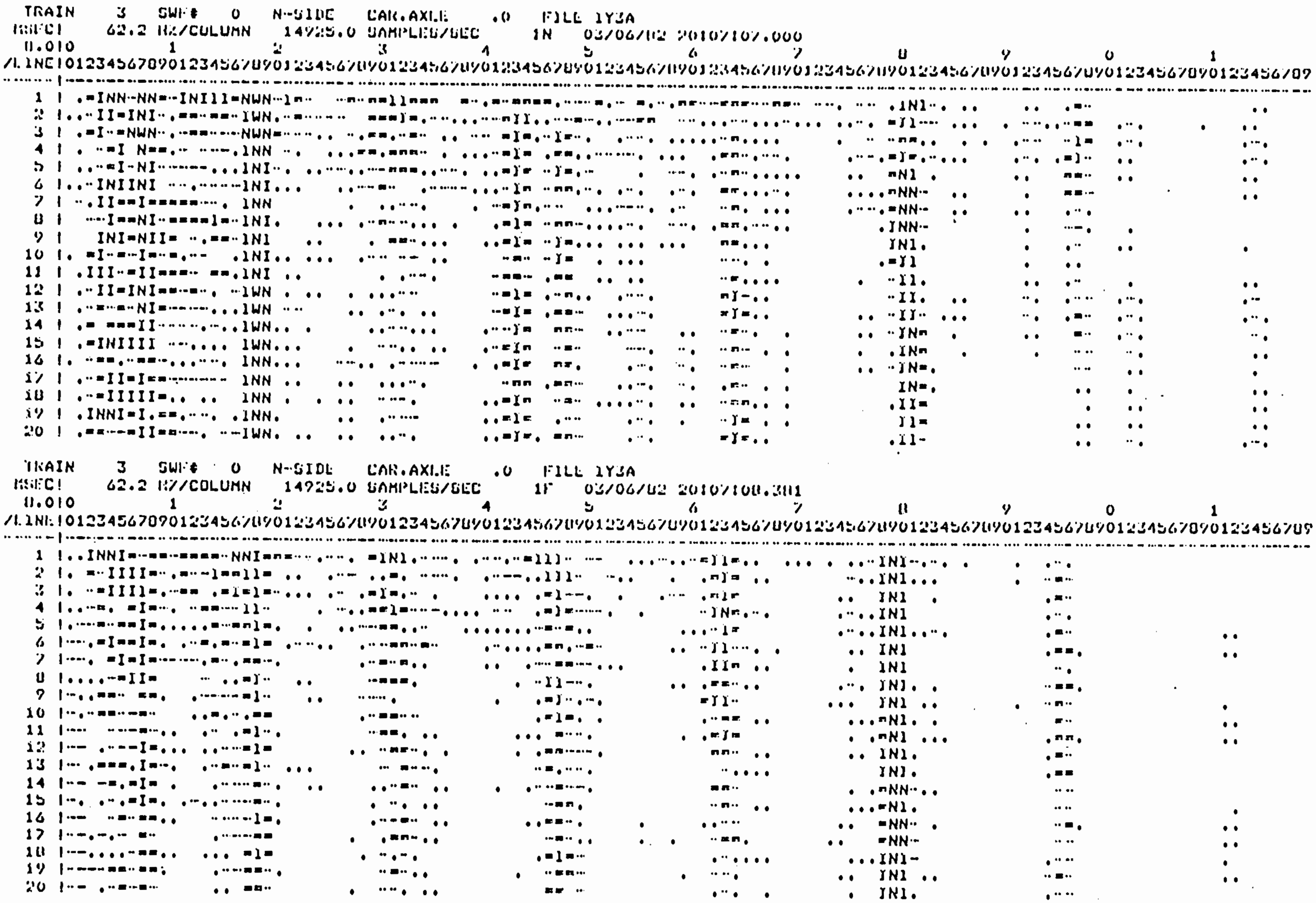


FIGURE 4.6 SPECTRA OF TWO SIGNALS FROM THE TEST CONSIST IN THE YARD

TRAIN NO. 3-HT-YD FILE: IY3A

REF. SIG. LEVELS (VRMS): 1.0000NS, 1.0000FS. 14925.0 SAMPLES/SECOND.

PLOT INFO: 180 FREQUENCY BINS, VER = .50 * (AMPL / THRES) ** 1.00.

DATA TAKEN ON HOSPITAL TRAIN NOT MOVING IN YARD.

FIGURE 4.6a PLOTS OF SIGNALS OBTAINED FROM THE TEST CONSIST IN THE YARD

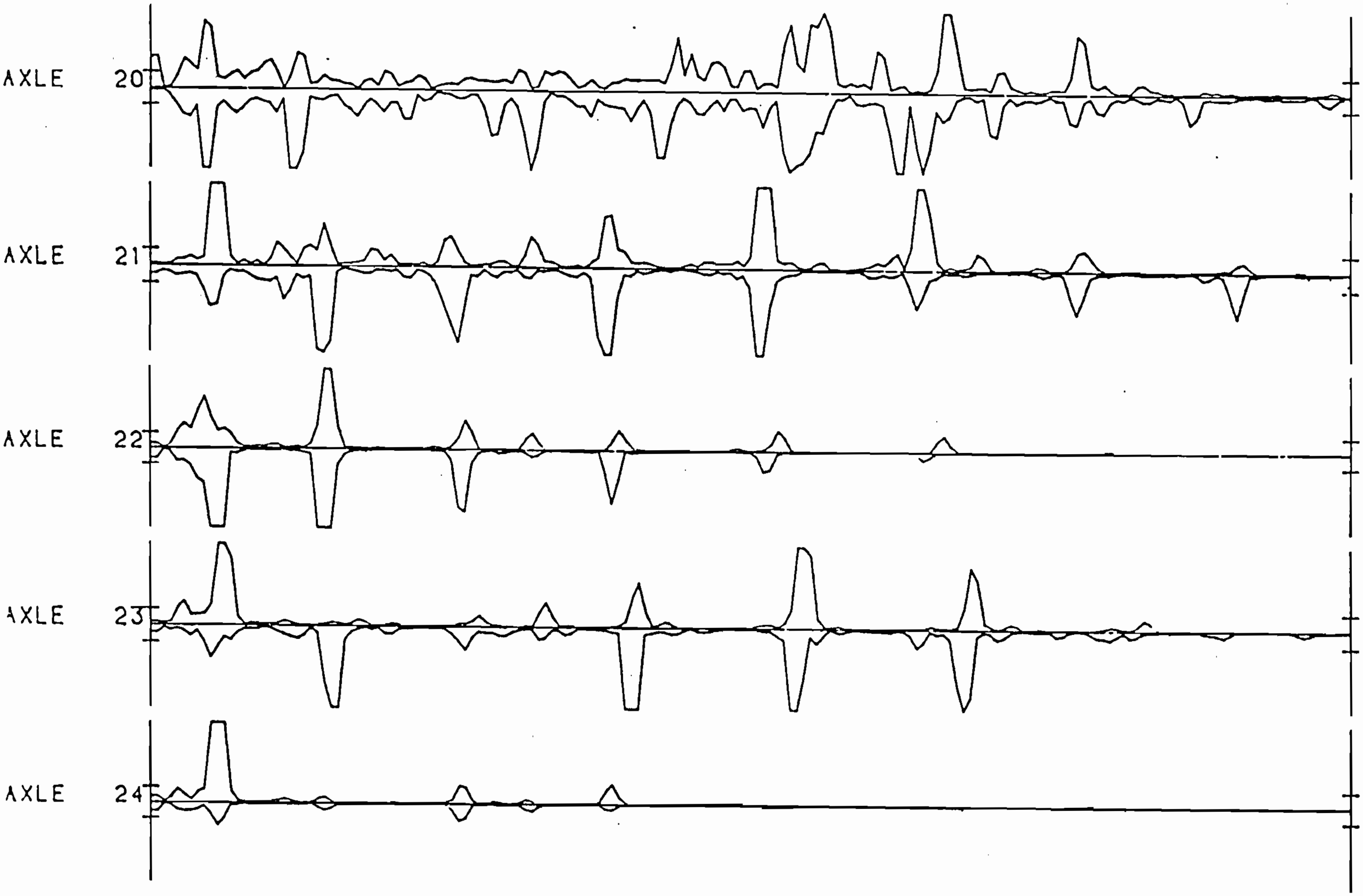


FIGURE 4.6b PLOTS OF SIGNALS OBTAINED FROM THE TEST CONSIST IN THE YARD

plot of a suspect wheel that was flagged during a revenue service train passage. The spectra of the two wheels on the axle ~~is~~ are considerably different.

Out of all the revenue train passage data, a bench mark train had to be chosen as a representative sample for experimentation. The criterion used in choosing such a train was that there should be a mimimum number of missing hits, preferably none, and that the signals obtained from the wheels should have very low noise content. The train passage that best met the criterion above was #292. The data from this train was ? processed in a manner similar to that used for the consist data. Fig 4.8 shows a histogram of percentage common peaks obtained for these this data. Using this variable as the indicator it is seen that the number of alarms is low. As in the previous case, one of the problems was the noise content in the signal.

The system is inactive now because it is being replaced with totally new equipment at the trackside. There has been a substantial improvement in the hammer design and wayside electronics. It is expected that once the new system is in operation, there will be a substantial improvement in the quality of data to be gathered. The studies made earlier on the setting of the discrimination levels should help in increasing the detection rate and lowering the false alarm rate. It is expected that the new algorithm will perform better on the actual train passages, and as more and more data is collected, a

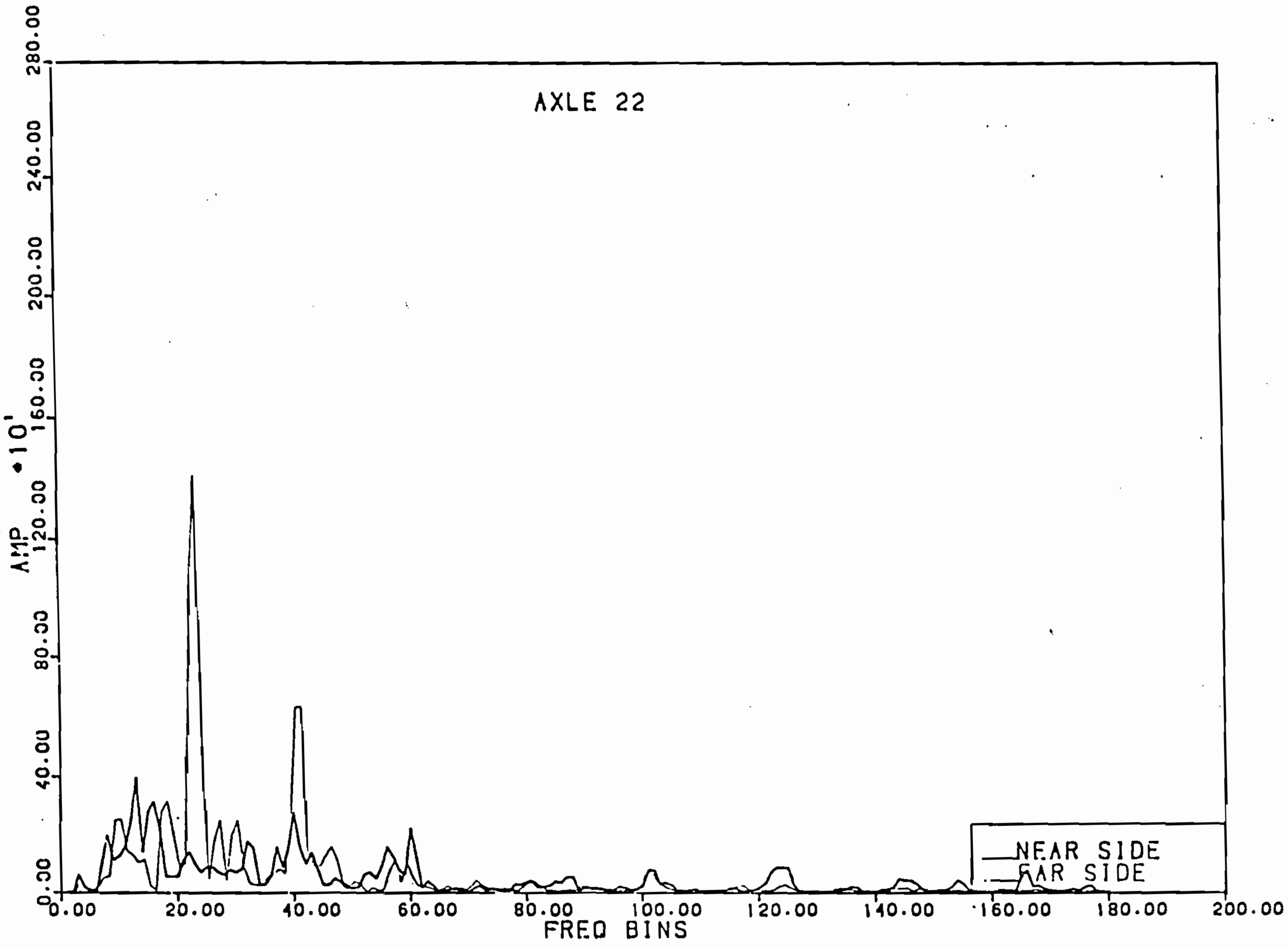
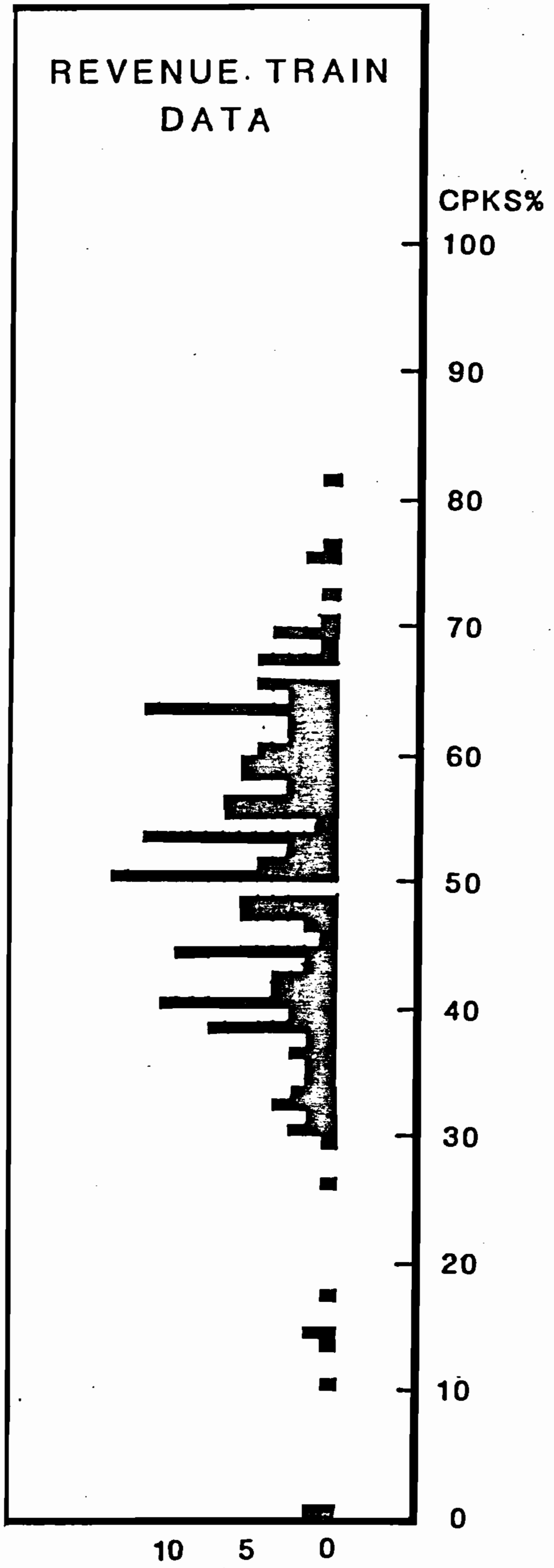


FIGURE 4.7 SPECTRAL PLOT OF A SUSPECT AXLE ON A REVENUE SERVICE TRAIN

FIGURE 4.8
HISTOGRAM OF PERCENTAGE COMMON PEAKS FOR A REVENUE SERVICE TRAIN (#292) (COMPARE FIGURE ~~4.8~~)
4.6



A900-1427-AW

better understanding of the characterstics of the alarm wheels is anticipated.

REFERENCES

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(3) Finch, R.D.,"Cracked Plate Detector Tests," Report to the Aerospace Corporation, 1980, with programmatic and technical commentary from F.D. Bruner and R.M. Vandeberg, Union Pacific Railroad Company, G.W. Brock and M. Dembosky, Ensco Inc., and E.L. Feigenbaum and G.J. McPherson, Aerospace Corporation.

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(7) Opinsky, A.J., "Railroad Wheel Back Rim Face Failures 1. Experience of Two Railroads over the Period 1973-1981,"AAR Report No. R-503, November 1981.

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Railroad Wheels," DOT Interim Report No. FRA-ORD&D-75-12, September 1974.

APPENDICES

APPENDIX 1

SYSTEM SPECIFICATIONS — [illegible]

CRC Bethany will design, assemble and provide start-up support for an Acoustic Signature Inspection System for Wheels on a line of the Southern Pacific Transportation Company at a site close to Houston.

This project will be done in phases. The first phase is the subject of this work in which the computer and associated special peripherals are not purchased. Instead, Southern Pacific will rent time on CRC Bethany's Real Time computer for this function.

The system will be designed to operate at 15 mph, and will not function at above 20 mph.

The system design will include the improvements recognized to be possible, as a result of experience over the past few years (time domain terms, recognition of greasy wheels, unevenly worn wheels, plate versus rim cracks).

A schematic of the system is included in Appendix 4.

Installation to be completed by December 1, 1981.

Information concerning wheel tests will be reported to Southern Pacific Operations in Houston using a telephone "hot line". The following will be reported:

"Suspect Axle
probably right/left side
suspect time/plate
date & time"

or

"train inspected:
no problem found
date & time"

The system consists of two major parts as shown: The data gathering and signal conditioning equipment at track side, and the data processing, analysis, and reporting service at the computer end.

Record of products of analysis, and signals for all bad wheels, and generous samples of good wheel spectra will be retained on magnetic tape for statistical analysis, and will be kept available for the funding partners.

Inspection limited to 200 cars/train. (locomotive wheels not included.)

During periods when the system is active, reports will be phoned to Southern Pacific Operations within 30 minutes.

10 minutes required between train passages.

Only in-bound trains will be inspected.

Standard 110 volt power will be required at wayside site.

Two hi-fi quality lines from the wayside site to Bethany's data processor are required, and will be provided by Southern Pacific.

An improved version of the Union Pacific hammer design will be used unless Southern Pacific makes a contract change to investigate their own hydraulic hammer design.

In the early phases of this project FRA will prepare analog tapes of banged wheel sounds from their T.T.C test station, if available.

FRA will supply any software improvements resulting from program at T.T.C.

APPENDIX 2

COMPONENT SPECIFICATIONS

1. Exciter

1.1 Produce vibrational excitation in the range of 0.2 to 8 KHz in all types of railroad wheels. The peak unweighted Sound Pressure Level at six feet must equal or exceed the background noise by at least 20 dB. Acoustic signatures resulting from the use of the exciter must be reproducible, independent of train speed or flange height and not contain resonances other than those of wheels in the frequency bands of interest.

1.2 Induce vibrations in the wheel from a point of contact low on the wheel's rim or flange. This point of contact shall be independent of the train velocity. The exciter shall impact the wheel only once.

1.3 Have an auxiliary power source (electrical or pneumatic) or be mechanically powered by the train. In the latter case, the exciter must not cause a vertical displacement of the wheel.

1.4 Excite wheels on both rails with train speeds of 1 to 20 mph. (Activation and resetting should not take longer than 170 msec.)

1.5 Not present a hazard to the train or to itself for train speeds up to 40 mph.

1.6 Be suitable for use under all weather conditions encountered at the site.

1.7 Be designed to comply with requirements for trackside apparatus now imposed by the Texas Railroad Commission.

1.8 Have a Mean-Time to Failure such as to allow operation for six months under normal conditions without probable failure.

1.9 Be capable of enablement and disablement under Wayside Electronics Control.

2.0 Wheel Proximity Detector

2.1 Produce a voltage pulse of 5-10V peak and 5 msec half-width every time a wheel pases over it.

2.2 Be capable of mounting or demounting to a rail in 15 minutes.

2.3 Be adjustable in sensitivity without remounting and preferrable by electrical adjustment.

2.4 Require sensitivity adjustment at no more than weekly intervals.

3.0 Microphone

3.1 Have a flat frequency response in the range 200-7500 Hz, at least.

3.2 Have a directivity and be located so that its response from a point source of 400 Hz moving in the path of the center of a wheel will be 12 dB down at 5 ft. beyond the excitation point.

3.3 Meet the clearance requirements of the Texas Railroad Commission.

3.4 Be secure from vandalism.

3.5 Require calibration and adjustment at no more than weekly intervals.

3.6 Be capable of operation in all types of weather likely to be encountered at the site.

4.0 Wayside Logic Control

4.1 Receive signals from the WPD's.

4.2 Actuate the Wheel Exciter under "ready" status advice from the computer.

4.3 Send a train motion fault alert to the computer.

4.4 Have automatic gain control to compensate for microphone signal level dependance on train speed.

4.5 Send two microphone signals to the computer.

4.6 Limit audio signals to the Communication line between +10 and -10 volts.

4.7 Supply power to microphone.

4.8 Match the impedance of the Hi-Fi lines.

5.0 Communications Link

5.1 S.P. to provide the following lines between the site and the computer.

5.1.1 Two one-way HiFi audio lines (site to computer).

5.1.2 Two voice grade telephone lines (one each way).

5.1.3 One regular telephone at site.

6.0 Signal Conditioning and Recording Unit (SCR)

This unit matches the communication lines to the CPU by providing signal isolation, frequency band filtering and envelope detection for the two audio signals, a clock for the analog-to-digital converters in the CPU, jacks to plug in a magnetic tape unit for recording and simulating the train audio signals, and a modulator and demodulator for the on/off signals tone encoded signals to and from the wayside. This unit includes the following:

6.1 Transformers for line matching and isolation of the two input hi-fi audio lines and the input and the output tone signaling lines.

6.2 Two frequency bandpass filters for limiting the signals going to the analog-to-digital converters (ADC). They should have a nominal 20 to 20,000 cps maximum range. The inputs should be compatible with both the transformers on the hi-fi audio lines and the output of the tape unit. The filter outputs should be compatible with the ADC inputs, the threshold detector inputs and the tape unit inputs.

6.3 Six jacks for connecting a protable tape unit (4 record and 2 playback). The playback jacks should open the normal circuit in from the bandpass filters and insert the playback signal at that point. The record jacks should be two at the ADC and envelope detector inputs and two at the output of the line matching transformer.

6.4 The tape unit should have at least two channels. The inputs should have enough sensitivity to properly record the signal at the input to the filter and at the ADC input. The input impedance should not load down either source by more than one dB. The tape unit's output should be capable of driving both the filters and the ADC and envelope detectors.

6.5 A TTL clock signal adjustable between 10,000 and 20,000 pps should be provided for clocking the ADC converters. It should be stable to better than 1%.

6.6 Two envelope detectors for detecting the beginning of the audio envelopes and interrupting the CPU so that it can cause the ADCs to start collecting about 170 milliseconds of data (at the above clock rate). The interrupt signals should be compatible with the external interrupt input.

6.7 A tone decoder and modulator unit should provide for sending two on/off signals (ready and fault) to the wayside from the CPU and receiving two signals (ready and fault) from the wayside. On the CPU end they should be compatible with the DIOs option A (TTL compatible) inputs and outputs.

6.8 Two remote indicator lamps and an audio signal should be provided to inform the computer operator that a routine or faulty-wheel report has been printed on the CPU's printer. A cancel button at the remote location should allow the audio signal to be stopped and a button at the printer's loncation should allow both lights and the horn to be turned off.

7.0 Computer Hardware

The computer accepts the audio data from the excited wheels, pairs the wheel data, analyzes it, determines suspected wheels, saves selected data, generates train reports, and in off-line mode allows analysis of data and adjustment of parameters. It includes the following:

7.1 The basic computer will be a Data General S130 Eclipse minicomputer with 128 KB memory, a 50 MB disk unit, a printer for the main (BG) console, a CRT for the foreground console, and a hardware floating point arithmetic unit.

7.2 Two analog-to-digital converter (ADC) channels capable of digitizing at least 4K samples of data at 20,000 samples/second. The two channels must be in dependently startable. The inputs should have a full scale range programmable between ±1 and ±10 volts or just a ± 5 volt range. The sampling clocks should be driven by a common source in the SCR unit. Suggested ADC boards are:

o DG 4151 + 4162 + 4160 ($4,500,w. Pgm Gain & DMA)
o DG 4333-A ($2,000.w. DAC's + 5V.)
o DATEC ST-NOVA 1D2C3C1 (+ 5V.,w. DAC's,$2,000)

7.3 A digital input/output (DIO) board is required to accept and generate on/off signals into and from the computer and to accept the envelope-detected signals to interrupt the CPU so that it can start the ADCs. The inputs and outputs should be TTL compatible and true (or on) when low (L). See the DG 4065 + 4066 documentation for interface details. The signals to be transmitted over this interface are the two ready signals, two fault signals, two envelope-detected interrupts, and the alert and priority signals to the computer operator.

8.0 Software Functions

The overall software functions are:

o To detect and report in a useful form a record of suspected bad wheels (with the particular fault criteria violated).

o To collect summaries of data and typical and exceptional data in order to refine the processing and discrimination programs.

More specifically,

1. Thresholds should be adjustable.
2. The hammers must be enabled or activated only when program is ready.
3. As much of the waveform (i.e. 170 ms) should be saved as is possible.
4. The processing of the data should be accomplished within 10 minutes of train passage.
5. The program should be able to abort collection on fast trains, reversing trains and trains passing during turn-on
6. The collected data should be:

o Written to disk

o Read from disk

o Enveloped

o Windowed

o Frequency transformed

o Compared and DI's computed

o Fault patterns, as specified in the proposal, classified and tabulated

o Faults reported

o Typical and exceptional data saved

o Checked for synchronization of wheels

Not all of these functions are done on every axle.

7. Reports should be printed for each train.

8. Disk space usage should be controlled so as to lose old data and reports rather than to overflow disk.

8.1 Data Acquisition Subsystem

This part of the program waits for the "clang" of the train wheels being excited, collects the waveform (about 170 milliseconds for each wheel at up to 20,000 samples/second), and stores this data on disk. It also maintains a directory for the disk storage, and will use the time data to identify the wheel pairs. The data, about 64K bytes per car, will be passed to the feature extraction program.

8.2 Feature Extraction Subsystem

The feature extraction part of the program accepts the waveform data from the data acquisition program (via the disk) and reduces the data for each wheel pair from about 8K samples of the waveform to less than about 100 numbers called features. It will operate mainly by converting the waveform data to the frequency spectrum and locating and measuring the resonances. Provision will be included for adding the determination of damping coefficients. These features extracted from the wheel data are passed to the pattern recognition programs.

The feature extraction algorithms should be possible, invariant with respect to the threshold and pattern recognition algorithms.

8.3 Pattern Recognition Subsystem

The pattern recognition program will examine the features extracted from the waveforms and catagorize the data into classes good, greasy, uneven wear, cracked tread, cracked plate, and no-test. The output from this classification procedure should be passed to the train report generator.

8.4 Reports Software output

The main real time report to be generated is the train passage report. The other reports are for system performance evaluation and further analysis of the collected data. All reports will include the identification information to remove ambiguity as to what they refer. The offline reports will set up to use parameters from the command line interpreter where ever possible. This will enable unattended operation for the production of time consuming reports. These offline operations will automatically be suspended as required for real-time processing. Where "selected train axles" are indicated for the reports, the specific axles may be specified by train number and axle number or a from-thru range may be specified or greater-than, less-than, equal, and not-equal criteria may be placed on the various features or other data in the features records.

8.4.1 Train Passage Report

The train passage report is generated as the train passes and the data is processed. It will appear on the printer approximately as shown below. The same data plus the thresholds and parameters used in making the determinations will be maintained in a disk file.

----------------------------TRAIN PASSAGE REPORT-----------------

Train Sequence No.________(1) Start of passage:HH:MM:SS MM/DD/YY

Axle No.(2)	Car/Axle No.(3)	Suspected Wheel (4)	Suspected Defect (5)	Inspection Report (6)

Axle Summary:

____________Suspected defects   End of passage:HH:MM:SS

____________Greasy wheels   End of Computation:HH:MM:SS

____________Unevenly worn wheels

____________Unclassified   Average Speed:________MPH

____________Good Wheels

____________Total Axles   Total Cars:____________

Notes: (1) Train number includes a direction and location suffix. (2) This axle number is counted one up starting with the first axle to pass to the last axle on the train. (3) The cars (including locomotives) will be counted based on about 6 rules for dividing axles into cars. The first axle on each car is number one. (4) Right or Left (facing forward). (5) Rim, plate or other exception. (6) The inspection column is for feedback from a visual or other type of wheel inspection. This inspection data will be linked back to the wheel data in the computer's files.

8.4.2 Plot of Waveform Envelopes for a Wheel Pair

The filtered, absolute amplitudes for the audio signals from a pair of wheels can be plotted by specifying the train and axle number . The envelope data will be plotted as bars of x's on the printer with time running downward. Bars for the left wheel will be plotted to the left of a centerline and those for the right, to the right of center. The time scale will be such as to fit the data onto one page.

8.4.3 Frequency Spectra for a Wheel Pair

The frequency spectra for any pair of wheel waveforms on file in the system can be plotted by specifying the train and axle number and the time domain window to be used. The spectra will be plotted as bars of x's on the printer with those for the left wheel extending to the left of the center and those for the right extending to the right.

8.4.4 Wheel-pair Analysis Details Report

This report will reperform the analysis on a pair of wheels and print all intermediate results leading to the final conclusion. The train, axle, and parameters file to be used will be specifiable. See Table 5 in the TTC report of Nov. '80 as an example.

8.4.5 Products-of-Analysis by Wheel-Pair

This report will print out the features (products-of-analysis) from the disk files by axle for selected train axles. See Table 4 of the TTC report of Nov.'80 for an example.

8.4.6 Histogram of a Product-of Analysis

This report will print a histogram of a given product-of-analysis (feature) for a selected group of train axles. See pp. 171 and 172 of D. Dousis' thesis for examples.

APPENDIX 3

Miscellaneous Utility Programs

ANFTIMES - Program to Analyze Waveform Times

ACARS - Program to Manually Assign Axles to Cars.

AVGPS - Program to Average Power Spectrums.

CRDTWO - Program to Convert Old "RD" Waveform files to new "WO" format

SGENO - Program to generate test scenarios for WACQ Test.

WFORM - Program to Copy Waveforms into Individual files.

Utility Subroutine Library (LIB).

This library includes all subroutines used in the SPW software of a generalized nature.

ADPAR.FP - Axle directory parameters.

ADSFX - Subroutine to add a file name suffix

BLANK - Subroutine to create a contiguous file without zeroing.

CCONN - Subroutine to create a contiguous file without zeroing.

CDPAR.FP - Car directory parameters.

CHATR - Subroutine to change file attributes

CHMSM - Subroutine to convert double integer milliseconds to hours, minutes, seconds, and milliseconds.

COMINIT - Special "CONINIT" for checkpoint program use

COPY - Subroutine to copy part of a line

CRDAY - Converts (RDOS) day number to year, month, and day

D2FDS - Decode from - through specification

DIFIX - Converts double integer to real and back

DKOD1 - Converts formatted number in a line to real

DKOD2 - Decodes formatted number in a line to real

DMSEC - Real funtion to return difference between double integer millisecond times.

DMYTR - Converts year, month, and day to (RDOS) Day number

DOTPR - Real function product

DW - Function returns real from an integer record

DWORD - Subroutine to store real within an integer record.

EHSID.SR - Marcros to emulate NOVA 3 instruction on Eclipse.

EXCCM - Subroutine used within OPCCM and WRCCM to Swap to program.

FGND - Subroutine to replace same from FLIB which doesn't work.

FMPYD - Integer multiply/Divide

GMSG2 - Gets AC2 message word from program start

GWFORM - Subroutine to get waveform from a data file

GWHEEL - Subroutine to get waveform from obsolete "RD" files

IBIT - Bit function to clear, test, and set bits.

INSTGM - Program to install patches to activate GMSG2 subroutine.

IPOS - Function to locate string in a line.

KISORT - Index sort subroutine

KHMSM - Subroutine to code double integer milliseconds into a line.

KNNAM - Codes number into a line

MKTNAME - Subroutine to make train file name from the train number.

OPCCM - Opens a COM.CM type file for use with WRCCM and EXCCM.

PRSPCT - Preconnection table for use with background data processing programs.

QTYVCTL - Subroutine to change QTY (asynchronous) line characteristics and rate

RBFILL - Subroutine to do right-blank fill

RLINE - Subroutine to read line for scanning

RSORT - Subroutine to Sort a real array.

SFPAR.FP - Waveform storage file (data-base) parameters.

SGRAM - Subroutine to display or print a spectrogram

SGRD - Program to print spectrograms form obsolete "RD" files

SPWERS.FP - Error codes used in SPW programs.

SWAOP2 - Subroutine to swap to another program, passing a message in "AC2"

WRCCM - Subroutine to write parameters and switches ito a COM.CM Type File.

Transform Subroutine Library (XLB)

This library contains subroutines for computing 6 Fourier as well as other transforms.

CFTG - Complex discrete Fourier transorms subroutine.

This subroutine can calculate discrete Fourier transforms or inverses on a complex array of any length. When the length of the array is not a prime number, the transofrm will be factored into a fast Fourier transform. The algorithm follows that of

Glassman, with changes to aviod the use of a sine table and to speed up the innermost loop.

CFTF - Complex discrete fast Fourier transform.

This subroutine allows the use of separate input and output array and a sine table calculated on the first call. It can calculate the Fourier transform or its inverse with or without the transposition required to reorder the complex frequencies.

This subroutine is about three times faster than CFTGH, taking .28 seconds for a 256 point complex transform.

RFTG - For analyzing a real array.

This subroutine accepts as input a real aray of time sample waveform values. Its output is a complex array of real andimaginary frequencies. No wirhgting is applied to the input array. It calls the subroutine CFTG.

RFTF - For Analyzing a Real Array.

This subroutine is similar to RFTF except that it sues subroutine CFTF.

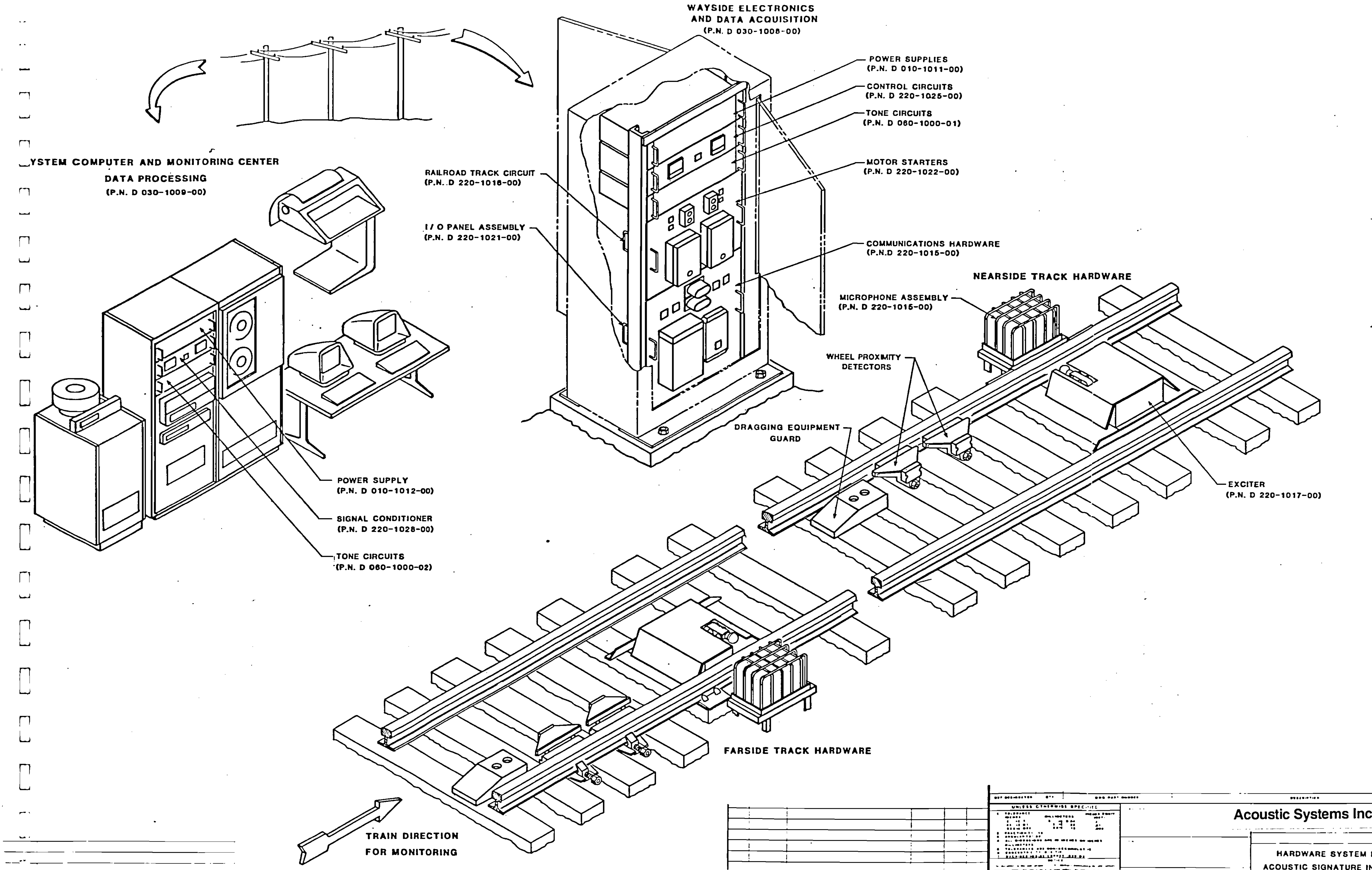
BFLY2 - "Butterfly" Subroutine used by CFTF.

This subroutine computes the basic interloop complex multiply and add function used by CFTF fast Fourier transforms.

CTPS - converts a pair of Waveforms to a power specturm.

This subroutine accepts a pair of wheel waveforms in an integer array and converts them to a power spectrum in an output array. Sine-squared windowing of the input data is used. Sensitivity parameters allow the output spectra to have units of volts squared.

APPENDIX 4



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HA 11 MAY 83

Acoustic Systems Incorporated

HARDWARE SYSTEM DIAGRAM
ACOUSTIC SIGNATURE INSPECTION

NONE
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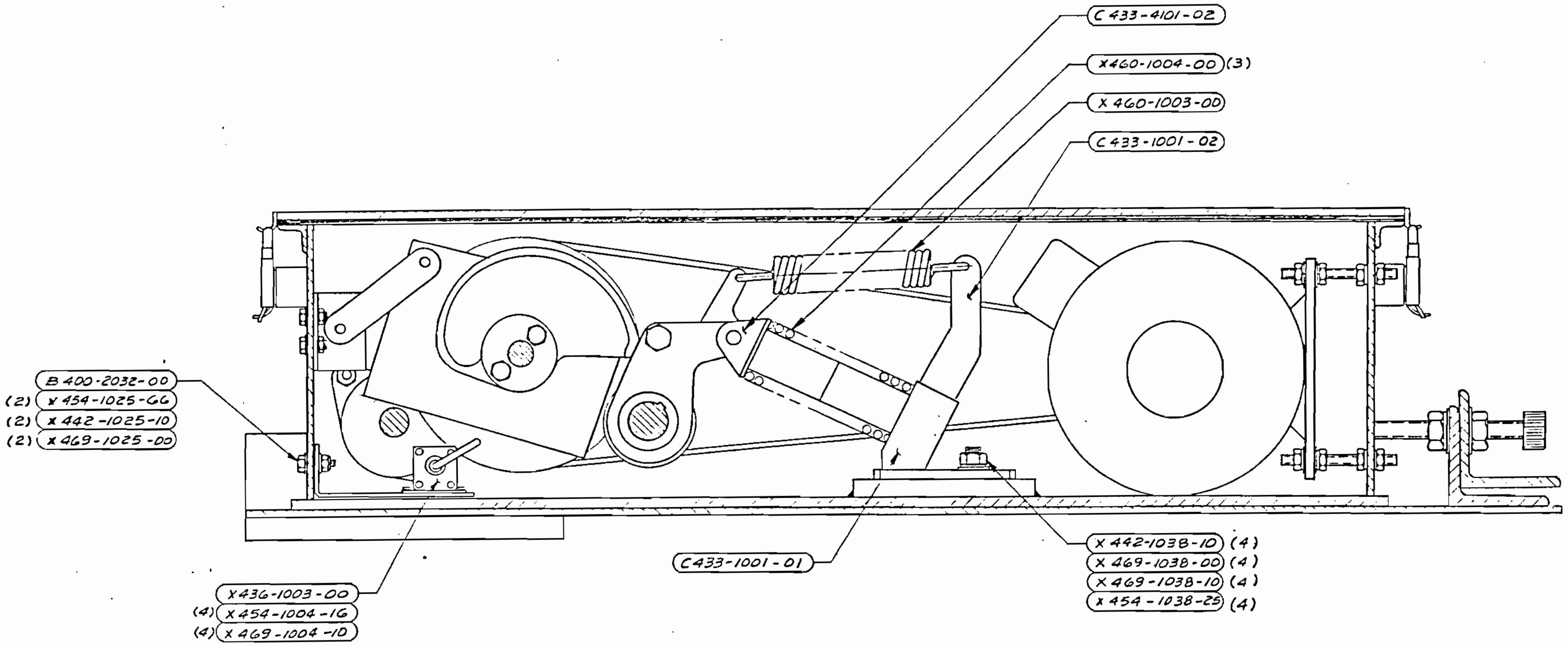
1 2 3 4 5 6

ASSEMBLY PROCEDURE

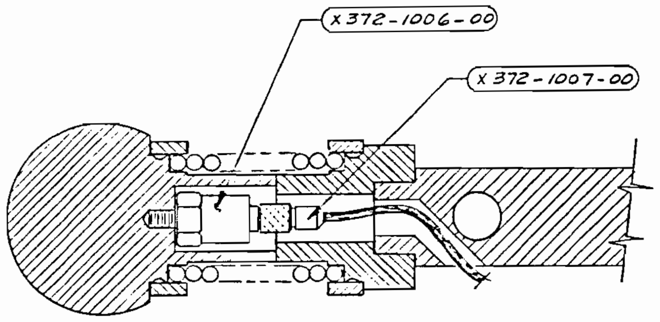
1. INSTALL THE SPRING ANCHORS (C433-1001-01) AND (C433-1001-02).
2. INSTALL THE SPRING SHAFT (D472-1014-01) AND SPRING ARM ASSEMBLY (C472-1013-0 ALIGN THE SPRING ARMS WITH THE SPRING ANCHORS. DRILL SPOT HOLES .250DI X.62 DEEP THRU SET SCREW HOLES.
3. INSTALL ALL THE DRIVE SPRINGS AND THEIR HARDWARE. SPRING (X460-1004-0 GUIDES (C433-4101-00) AND RETURN SPRING (X460-1003-00).
4. INSTALL THE MECHANICAL COUNTER (X436-1003-00).
5. INSTALL THE CLUTCH (X308-1001-00), SHAFT (C433-7801-02), CAM (C433-2502-00), AND THEIR HARDWARE.
6. ATTACH THE CAM FOLLOWER (X401-1007-00) AND ADJUST THE CAM TO MATCH.
7. INSTALL THE CLUTCH ANCHOR (B433-1503-00) AND LINK (B400-2021-0
8. INSTALL THE IDLER SHAFT (D472-1014-02) AND ALIGN ARMS ON SHAFT ENDS.
9. INSTALL THE MOTOR (X348-1001-00) ALIGNING MOTOR PULLEY (X402-1003-00) AND BELT (X402-1004-00) WITH THE CLUTCH PULLEY (C402-1005-00).
10. AFTER INSTALLING SWITCH, (X366-5016-00) IN CABLE GLAND CONNECTOR (X448-2011-05) SOLDER THE TWO WIRE LEADS ON SWITCH TERMINALS. POT REAR OF CONNECTOR WITH EPOXY POTTING COMPOUND, (X530-1005-00) AND (X530-1006-00).
11. WIRE CLUTCH, (X308-1001-00) FROM TERMINAL BLOCK USING WIRE. ORANGE WIRE (X381-1806-00).
12. COMPLETE ASSEMBLY.



SECTION A-A

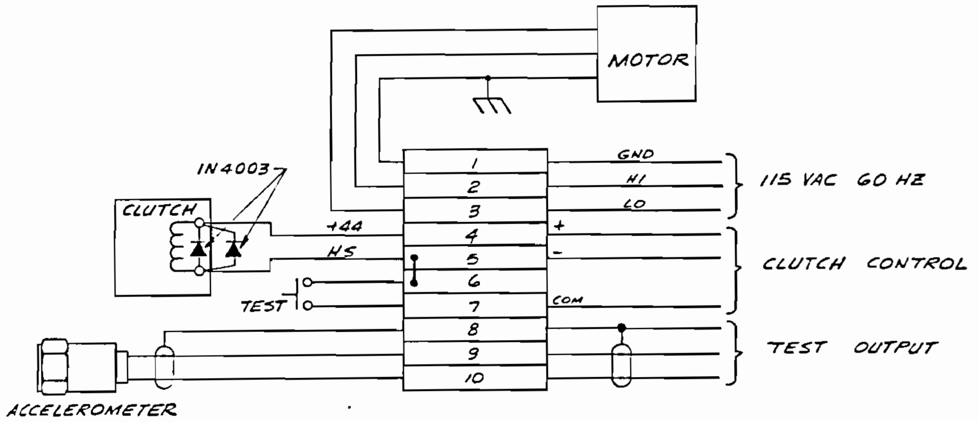
ADJUSTMENT PROCEDURE

1. ROTATE THE CAM TO RELEASE THE FOLLOWER.
2. ADJUST THE SPRING ANCHORS SO THE BALL WILL BE IN IT'S STRIKE POSITION, 2.40 INCHES FROM FRONT SURFACE OF HOUSING WALL TO THE FRONT SURFACE OF THE BALL.
3. CAREFULLY ROTATE THE CAM TO PUSH TO FOLLOWER TO IT'S MAXIMUM COCKED POSITION. CHECK TO ASSURE THAT THE SPRING INNER GUIDES DO NOT BOTTOM.
4. ADJUST THE BELT TENSION WITH THE MOTOR MOUNTING BOLT.
5. ADJUST CLUTCH ANGLE SO THAT THE CAM FOLLOWER STOPS 1/4" FROM THE END OF THE CAM. (THIS ADJUSTMENT MAY NEED TO BE REPEATED AFTER HAMMER INSTALLATION).



DETAIL - B

SCALE = FULL



WIRING DIAGRAM

REV	ECN #	DESCRIPTION	DATE	BY	CHECKED
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A	—	RELEASE	30JAN83	HA	

REF DESIGNATOR | QTY | DWG PART NUMBER | DESCRIPTION

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MATERIAL ~

FINISH ~

DRAWN HA DATE 31 JAN 83

APPROVED DATE 2-9-83

CHECKED GMC DATE 2-9-83

APPROVED GMC DATE 2-9-83

Acoustic Systems Incorporated

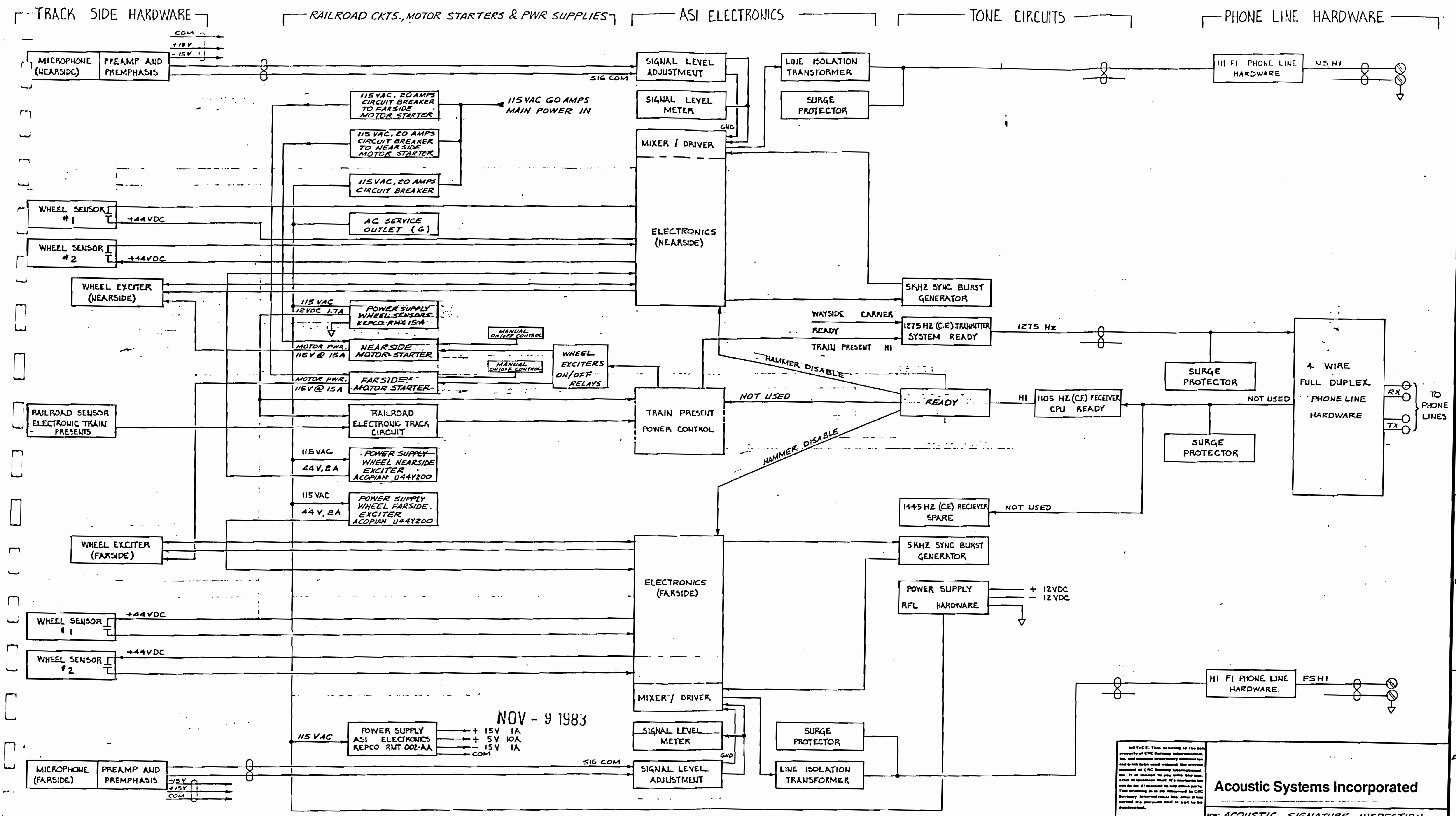
EX-2

TITLE ASSEMBLY EX-2 EXCITER

SCALE 1 = 2

D 220-1017-00

REV B



NOV - 9 1983

Acoustic Systems Incorporated

FOR: ACOUSTIC SIGNATURE INSPECTION

BLOCK DIAGRAM
WAYSIDE ELECTRONICS

DRAWN BY d' dimey DATE 1-20-83
DESIGNED BY
CHECKED BY
JOB ENGR
PROJ ENGR
CLIENT
PRINT

SHEET 1 OF 1
SCALE NONE
DRAWING NO. D 030-1008-BL
REV △

NOTES FOR MECHANICAL DRAWINGS
UNLESS OTHERWISE NOTED:
.X ± .05
.XX ± .02
.XXX ± .005
ANGULAR ±
FINISH IN MICROINCHES

LTR.	ZONE	REVISIONS	DR. CHK.	APP.	DATE	LTR.	ZONE	REVISIONS	DR. CHK.	APP.	DATE	NUMBER	REFERENCE DRAWINGS
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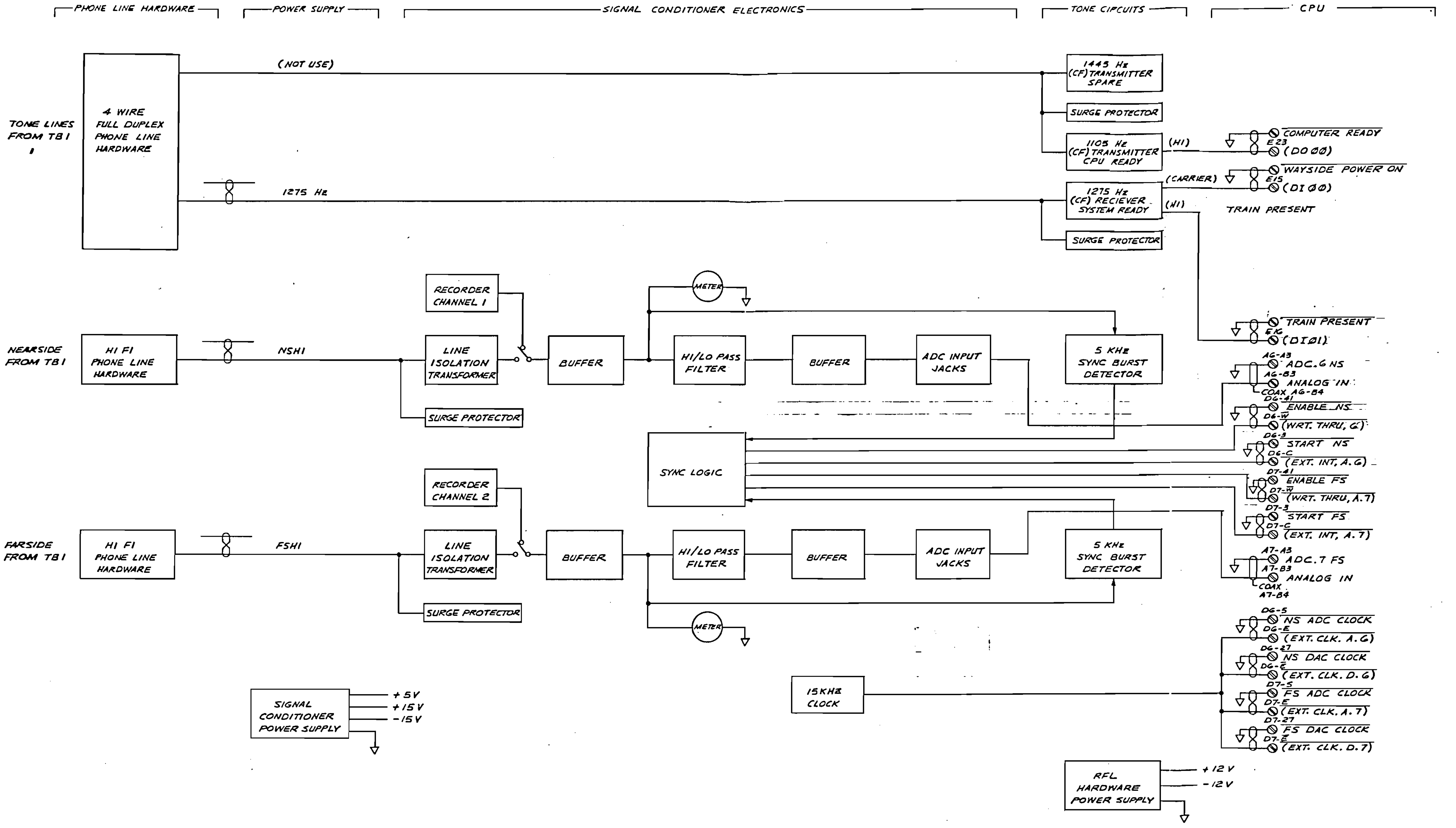


NOV - 9 1983

REV		DESCRIPTION	DATE	BY
A		RELEASE		HA

UNLESS OTHERWISE SPECIFIED

MATERIAL ~

FINISH ~

DRAWN HA DATE 4-20-83

CHECKED

APPROVED

Acoustic Systems Incorporated

FOR ACOUSTIC SIGNATURE INSPECTION

TITLE
BLOCK DIAGRAM
SIGNAL CONDITIONING ELECTRONICS

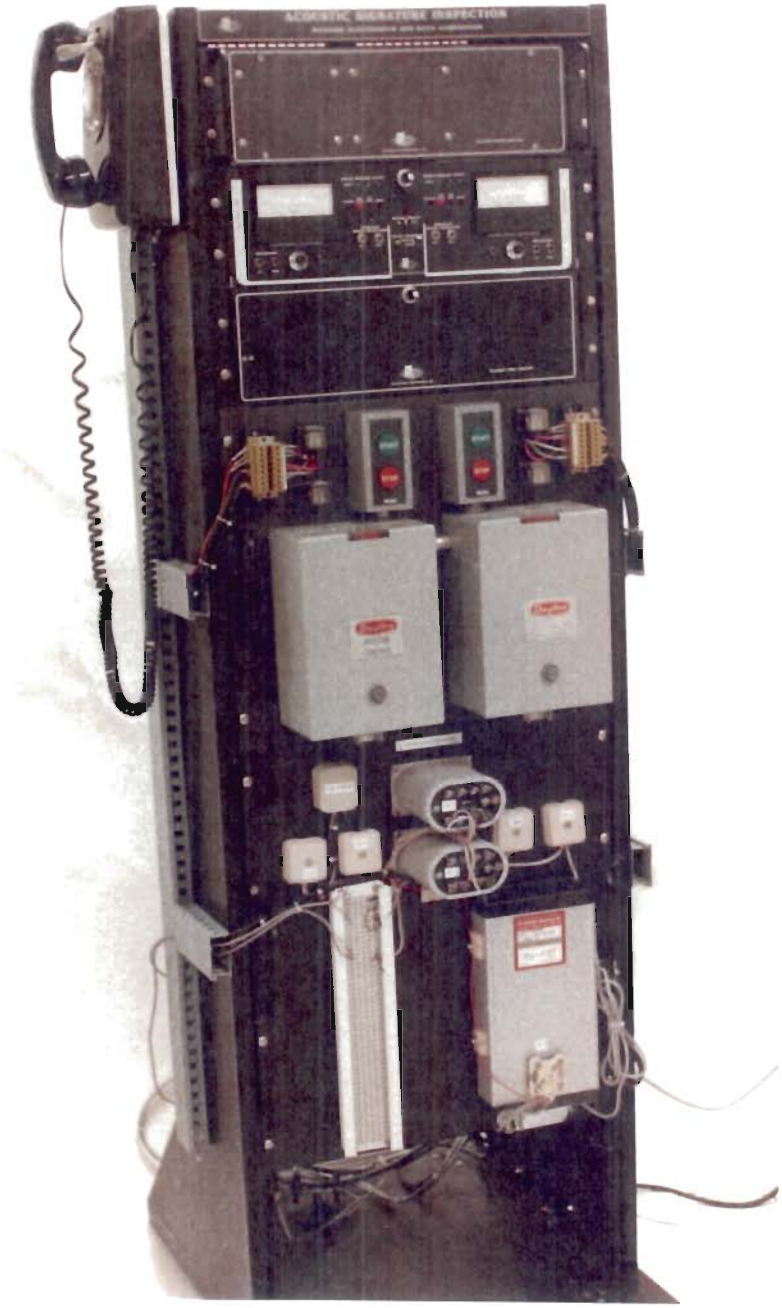
SCALE NONE

SHEET 1 OF 1

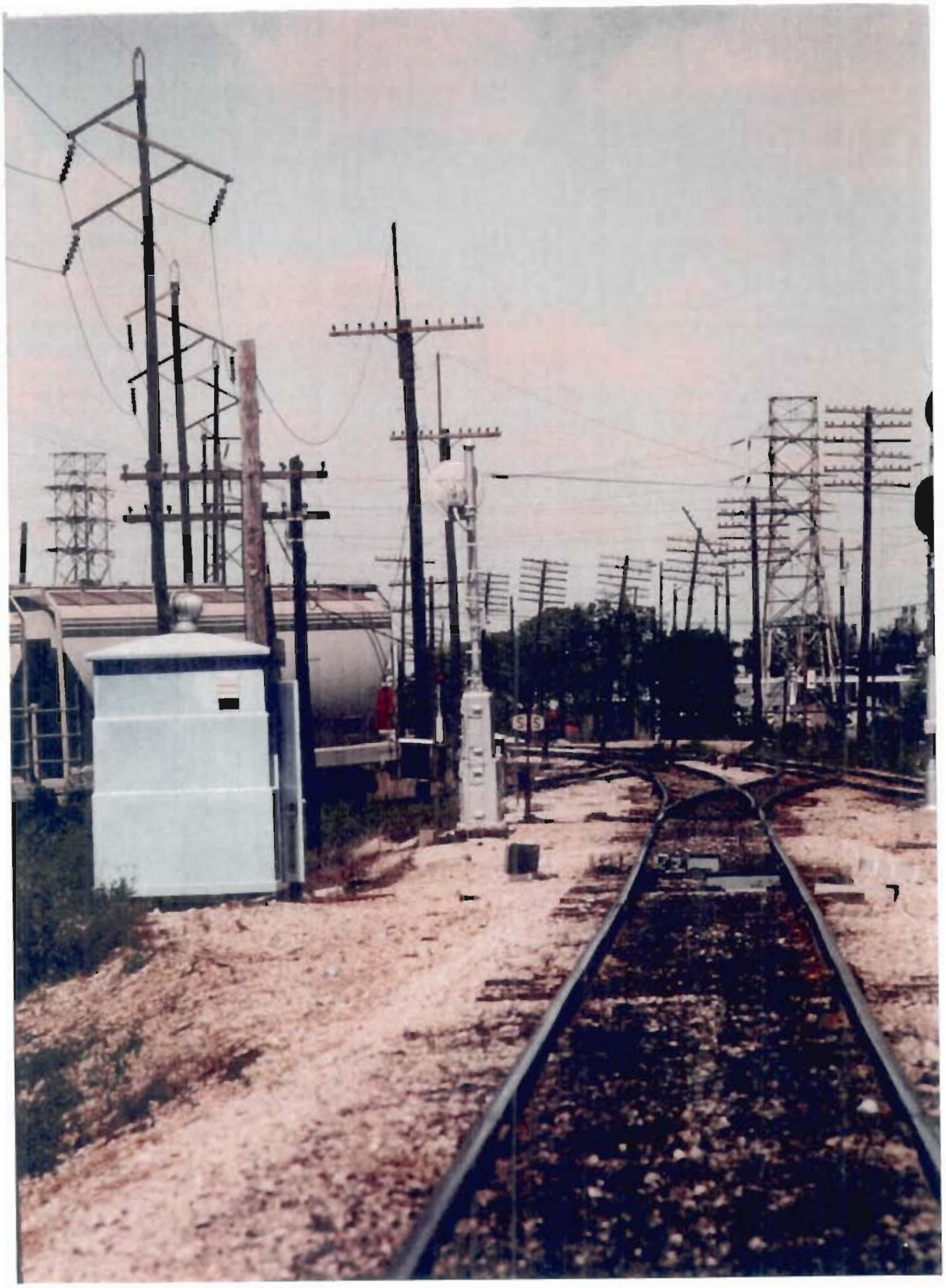
DWG PART NUMBER D 900-1180-00

REV A

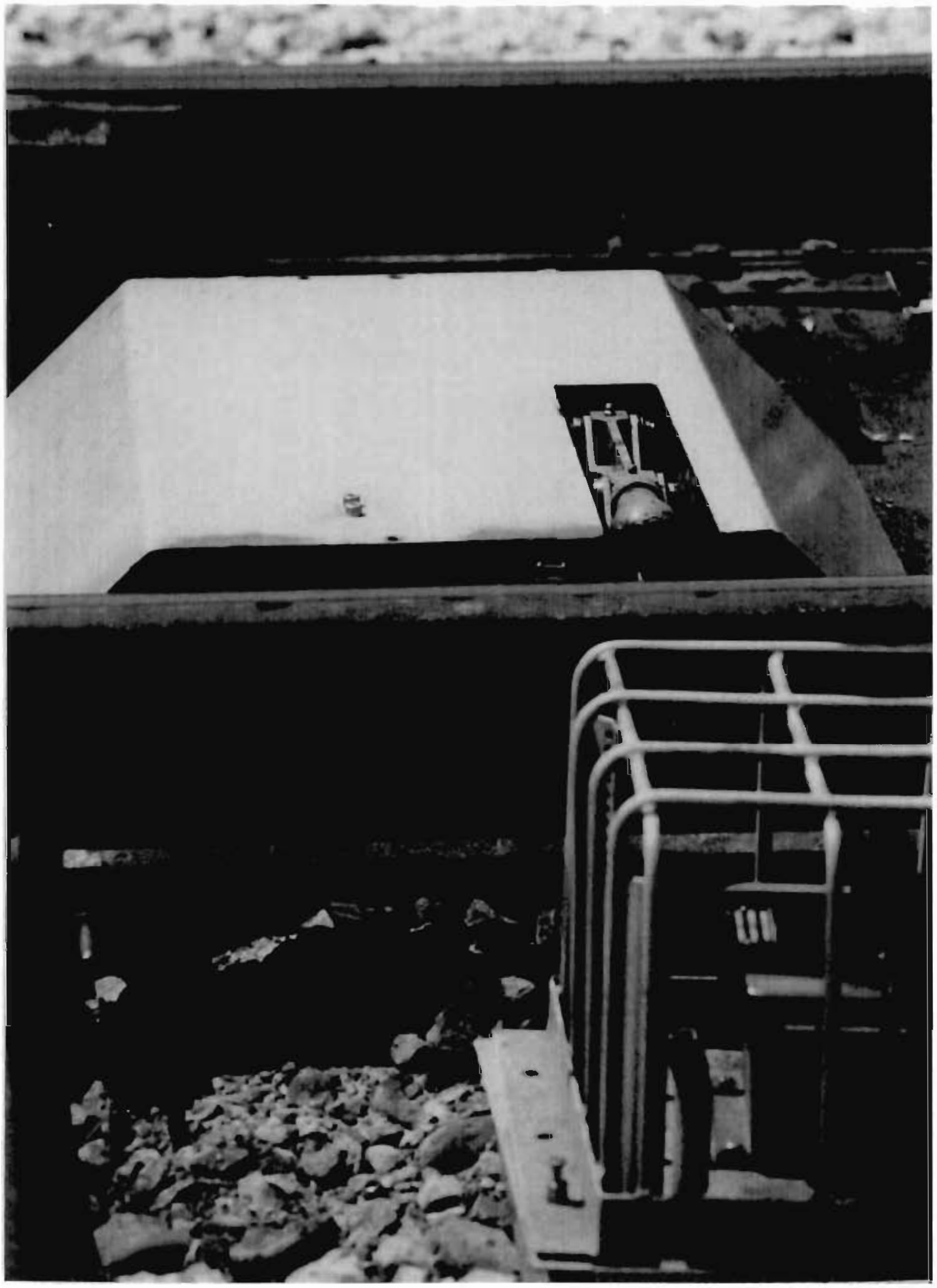
APPENDIX 5



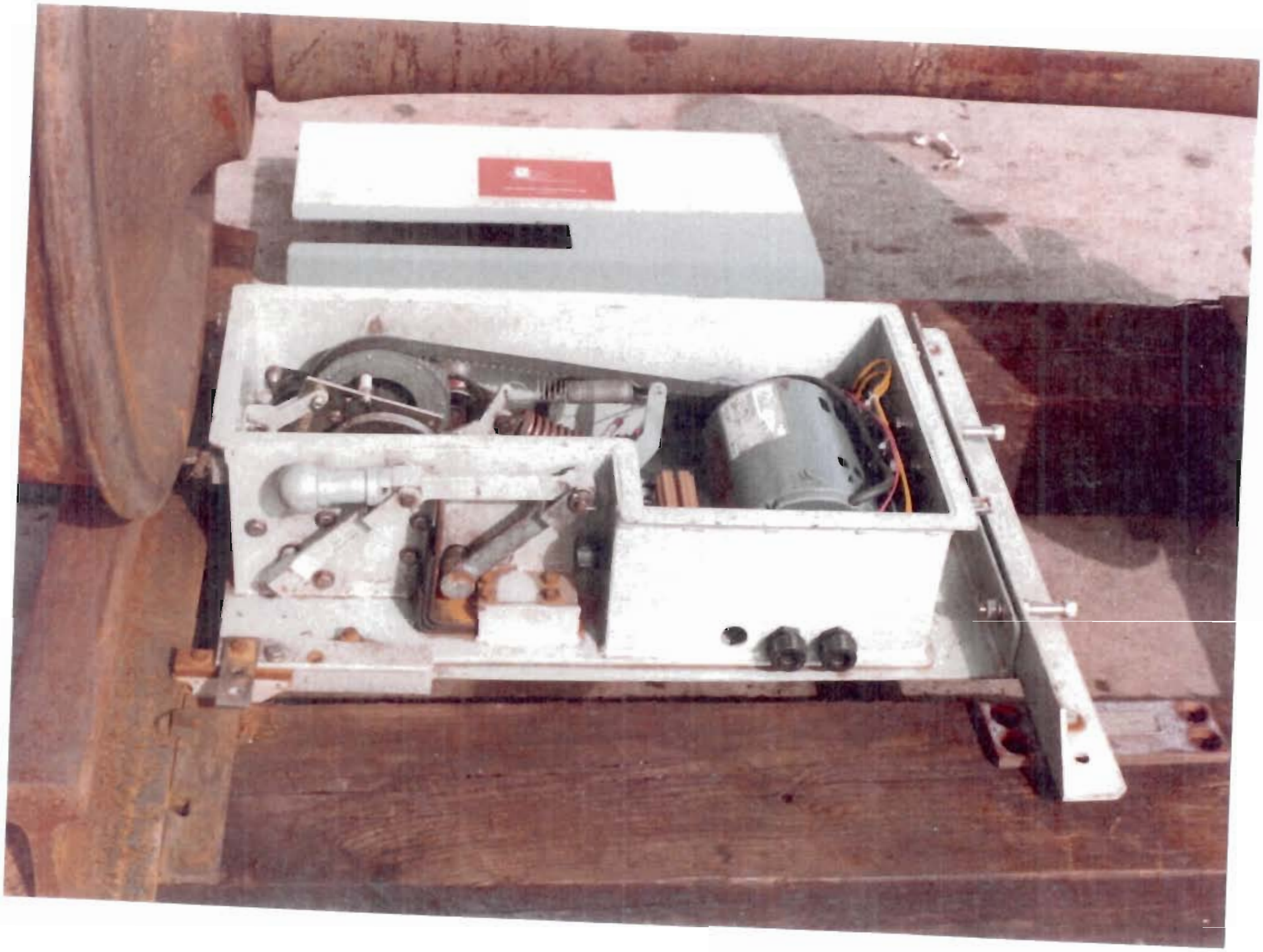
WAYSIDE ELECTRONICS



INSPECTION SITE



HAMMER AND MICROPHONE



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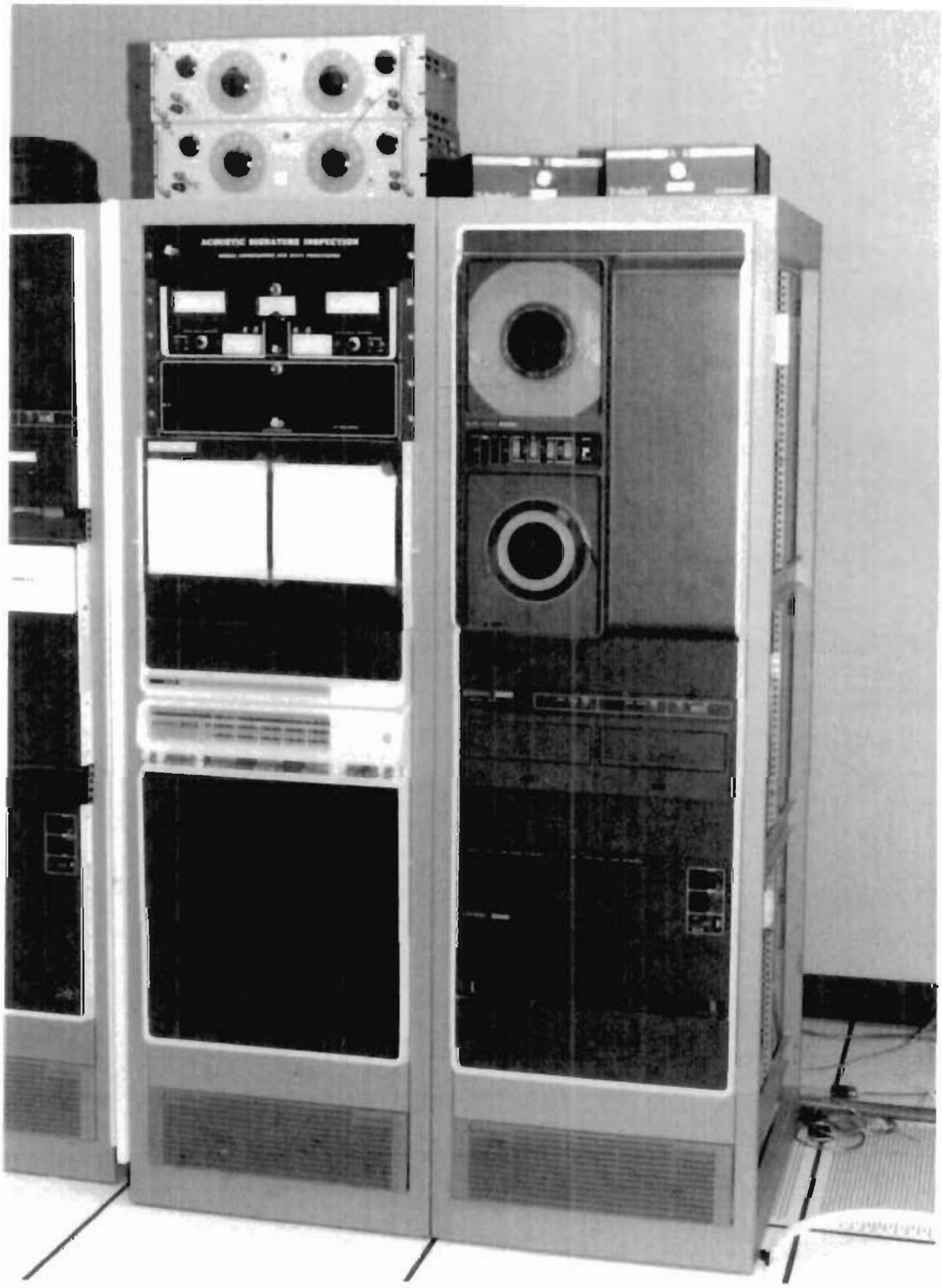

COMPUTER

FOREGROUND AND BACKGROUND

TERMINALS