A PROFILE MEASURING, RECORDING, AND PROCESSING SYSTEM

by

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Research Report Number 73-2

Development of a System for High-Speed Measurement of Pavement Roughness

Research Project 3-8-63-73

conducted for

The Texas Highway Department

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

April 1970

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

PREFACE

This is the second in a series of reports covering the results of Research Project No. 3-8-63-73, "A Feasibility Study for High-Speed Road Profilometer Equipment." The project was initiated in 1963 for the purpose of evaluating the existing roughness measuring devices and providing to the sponsors a recommendation as to the best existing system for accurate measurement of road profiles. In the first report, 73-1, "High-Speed Road Profile Equipment Evaluation," the General Motors Road Profilometer was recommended and after authorization from the Bureau of Public Roads a contract was initiated with the company licensed to manufacture it.

The profilometer, called the Surface Dynamics (SD) Profilometer, was manufactured by K. J. Law Engineers, Inc., and was delivered to the Texas Highway Department on February 6, 1967. Evaluation began immediately and this report provides the results of these evaluations and describes the resulting measurement system.

Support for this project was provided by the Texas Highway Department and the U. S. Transportation Department Bureau of Public Roads. The assistance of Texas Highway Department Contact Representative Kenneth Hankins is especially appreciated.

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April 1970

LIST OF REPORTS

Report No. 73-1, "High-Speed Road Profile Equipment Evaluation," by W. Ronald Hudson, presents a review of existing roughness measuring equipment and recommends the GM Profilometer as the most promising of all available equipment for high-speed profile measurements.

Report No. 73-2, "A Profile Measuring, Recording, and Processing System," by Roger S. Walker, Freddy L. Roberts, and W. Ronald Hudson, presents a description of the Surface Dynamics Profilometer profile measuring system, an operating procedure for use with the equipment, and a system analysis procedure for validation of the profile data.

ABSTRACT

A description of the Surface Dynamics Profilometer measuring system is included in this report. The objective of this system is to provide the Texas Highway Department with the capability to measure and evaluate highway profiles. The profilometer measuring system is composed of two road-following wheels mounted on trailing arms beneath a vehicle, one in each wheel path. The wheels are held in contact with the road by a 300-lb spring force. The relative motion between the vehicle and the road-following wheel is measured by a potentiometer while the accelerometer measures the acceleration of the vehicle body. These signals are input into a special purpose analog computer carried in the measuring vehicle. The computer integrates the acceleration signal twice and adds to it the potentiometer signal. This signal is conditioned, depending on the filter selection, to make the right and left profiles. Since these data are in analog form, and digital processing was considered desirable, an analog-to-digital program was developed. It is described in detail.

An operating procedure for use with the profilometer is presented along with detailed calibration procedures for both the profile computer and the sensing devices.

An analysis of the system includes an experiment which was conducted to check the authenticity of the calibration signals, the errors in the digitization process, and verification of the overall frequency-response of the system.

KEY WORDS: Surface Dynamics Profilometer, profile, surface evaluation. roughness, frequency response, resolution, analog-to-digital process.

TABLE OF CONTENTS

NOMENCLATURE

va	=	volt-amps
hz	=	Hertz
vdc	=	volts direct current
Khz	=	Kilo Hertz
vpi	=	volts per inch
db	=	decibels
FM	=	frequency modulation
bpi	=	bits per inch
rpm	=	revolutions per minute
ma	=	milliamperes
TP	=	test points for computer cards
ω	=	frequency in radians per second

CHAPTER 1. INTRODUCTION

GENERAL SYSTEM DESCRIPTION

The high-speed road profile measuring system described in this report provides a quantitative measure of a road profile. This measure may be acquired at selectable speeds up to 60 miles per hour and thus can be used without undue interference with traffic for obtaining high-speed road profile measurements. Figure 1.1 depicts a general block diagram of the profile measuring system described herein. Two major subsystems are indicated in this figure, the Surface Dynamics (SD) Profilometer (trade name for the GMR Road Profilometer) and the analog-to-digital (A-D) subsystem.

The SD Profilometer (see Fig 1.2) was originally developed by General Motors Corporation to obtain analog profile data for use in vehicle ride simulation for research purposes. However, because of the widespread interest in the device, General Motors Corporation in 1966 licensed K. J. Law Engineers, Inc., to manufacture the SD Profilometer. The SD Profilometer described herein was the first such unit delivered by Law.

Data processing for the system can be pursued in several ways, including analog processing or digital processing. The analog processing has advantages when a digital computer is unavailable and only processing techniques such as harmonic analyses and power spectral density are desired. However, other techniques such as variance of slope or roughness indices are more difficult to obtain in analog data form and lend themselves to digital processing. Because of the availability of a digital computer and the resulting increased flexibility, digital processing was chosen for this system.

The analog profile data obtained from the SD Profilometer are digitized for use in analysis. The A-D subsystem consists of an SDS 930 general purpose computer with an analog-to-digital peripheral unit owned by The University of Texas. A second A-D unit has been purchased for use with the system by the Texas Highway Department and will be discussed in Research Report 73-4.

This report is divided into six chapters and two appendices. Chapter 2 provides a detailed description of the profile measuring system and subsystems.

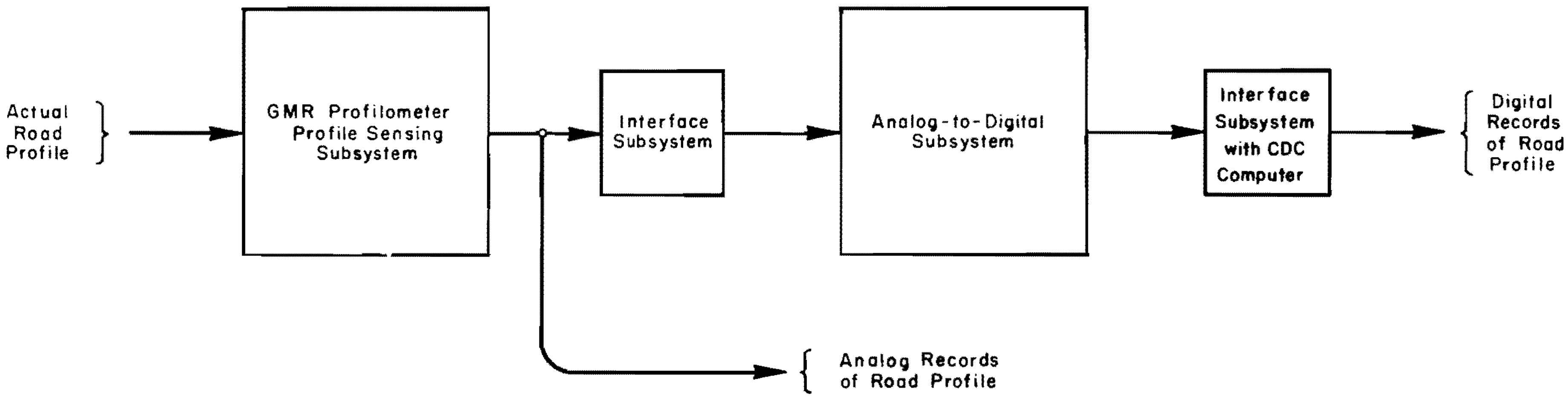


Fig 1.1. Profile measuring system.

Fig 1.2. Surface Dynamics Profilometer.

Chapter 3 explains the general operating and calibration procedures for obtaining profile measurements, and Chapter 4 describes the system analysis that has thus far been performed to establish the accuracy in the measurement process. Chapter 5 presents a summary and the conclusions while Chapter 6 suggests applications for the research results. Appendix 1 lists the problems encountered and the solutions used in obtaining a workable profile measuring system. Appendix 2 includes the SDS 930 A-D program listing.

SYSTEM OBJECTIVE

The objective of the high-speed road profile measuring system is to provide the Texas Highway Department with the capability to measure highway profiles at high speeds and to evaluate them. These road profiles are useful to the State for such diverse purposes as evaluating the serviceability index of new or existing pavements, establishing pavement maintenance priorities, conducting research such as determining whether continuously reinforced concrete pavements provide better serviceability than jointed pavements, and possibly, ultimately, establishing roughness levels for acceptance of new construction.

CHAPTER 2. SYSTEM DESCRIPTION

GENERAL

This chapter describes the SD Profile Measuring System and its basic operation. An example of the typical measuring process is provided along with a detailed description of each of the major subsystems.

In order to determine the road profile for a particular section with the profile measuring system, the standard measuring procedure is as follows:*

(1) Drive the SD Profilometer to the pavement section to be measured.

(2) Determine filter-speed combinations and calibrate the electronic equipment.

(3) Drive the profilometer over the pavement section, thus obtaining the road profile measurement.

(4) Examine the visual hard copy strip chart output of the road profile.

At this point the road profile has been obtained in a continuous form on the strip chart recorder, providing a permanent visual record of this profile, and/or on the analog magnetic tape recorder. If a digital record of this profile is desired, the analog tape is returned to the laboratory where the analog road profile measurements are converted to discrete digital values at the desired equidistant intervals by the A-D subsystem. Computer programs may then be used to summarize these data in the required form for subsequent profile analysis. Figure 2.1 illustrates this procedure.

The SD Profile Measuring System provides a quantitative measure of a roadway profile in analog or digital record form. These records may then be used directly with an analog or digital computer for roadway analysis. The SD Profilometer vehicle contains the necessary sensors and instruments to obtain the profile measurements in analog form at speeds up to 60 mph. The A-D subsystem is then used to convert the analog profile signals into digital form for digital computer analysis. Current A-D subsystem operations have centered around an SDS 930 computer.

*See Chapter 3 for the complete operating procedures.

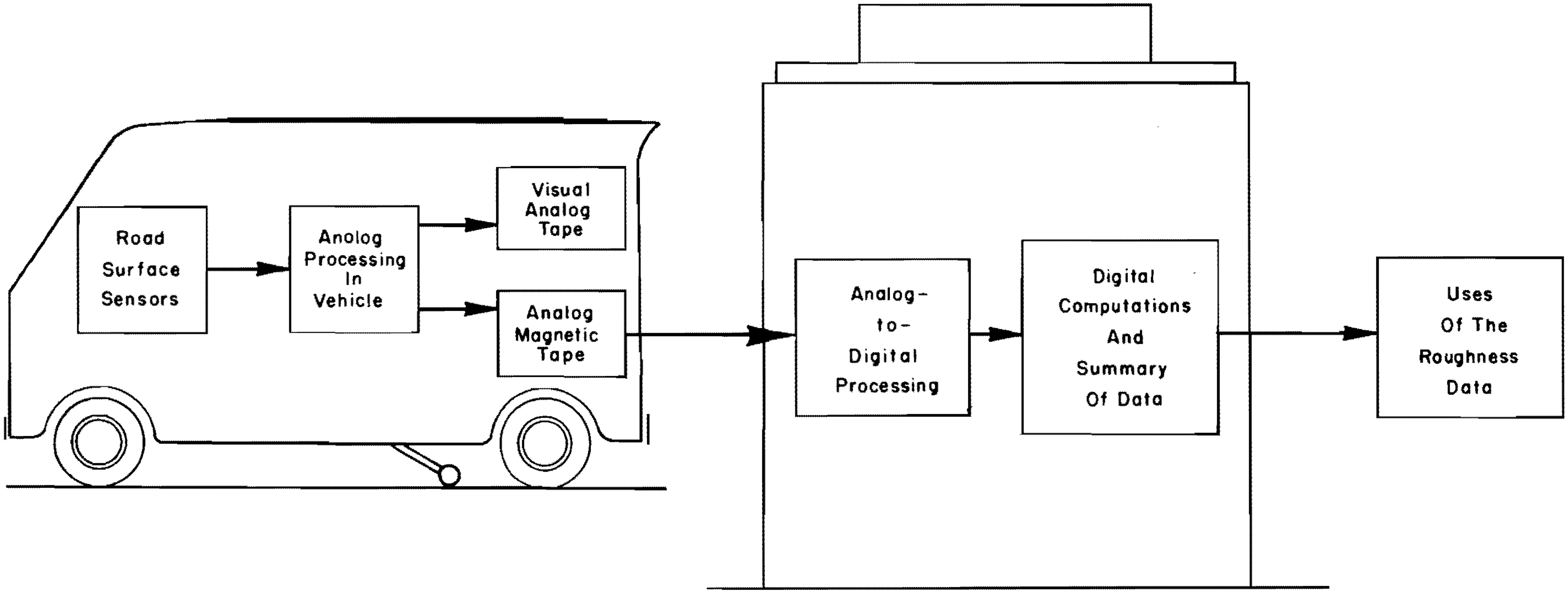


Fig 2.1. Measurement process.

A detailed block diagram of the SD Profile Measuring System is depicted in Fig 2.2.

SD PROFILOMETER SUBSYSTEM

Measuring Technique and Equipment

The SD Profilometer vehicle contains all the necessary sensors and equipment to obtain an analog signal directly proportional to a roadway profile. To accomplish this a small road-following wheel (which is mounted to the vehicle and held firmly in contact with the road by a 300-pound spring force exerted by a torsion bar), a linear potentiometer, an accelerometer, and a small analog (profile) computer are used to sense and record data as indicated in Fig 2.2. The linear potentiometer is mounted between the sensor wheel and the vehicle body. The difference in sensor wheel and vehicle body displacement $W-Z$ is obtained by the potentiometer. The accelerometer, mounted directly above the potentiometer, induces a voltage proportional to the vertical acceleration $\ddot{Z}$ of the vehicle body. The analog computer double integrates the vertical body acceleration thus obtaining vertical body displacement Z. A voltage directly proportional to the vertical wheel movement and thus the road profile is then obtained by the analog summing of the vertical body movement Z and the body and sensor wheel displacement difference $W-Z$. An active high pass filtering network is employed in the integrator and summing circuitry for filtering low frequency or long wavelength profiles (hills, etc.). Two independent measuring subsystems are used for both right and left profile measurements. Reference 1 should be consulted for further details of the measuring technique.

The sensor device used to measure the difference in wheel and body displacements is a Markite linear potentiometer. This high quality potentiometer is considered by the Markite Company to have "substantially infinite" resolution. The potentiometer is excited with a regulated 15-volt power supply. The potentiometer output signal is scaled in the profile computer so that a one-inch displacement of the potentiometer shaft is equivalent to one volt.

Vertical vehicle body acceleration is obtained with a Systron-Donner model 4310 servo accelerometer (see Fig 2.3) that has a ±2 g range. The output from this accelerometer is large enough so that signal amplification in the profile computer is not necessary.

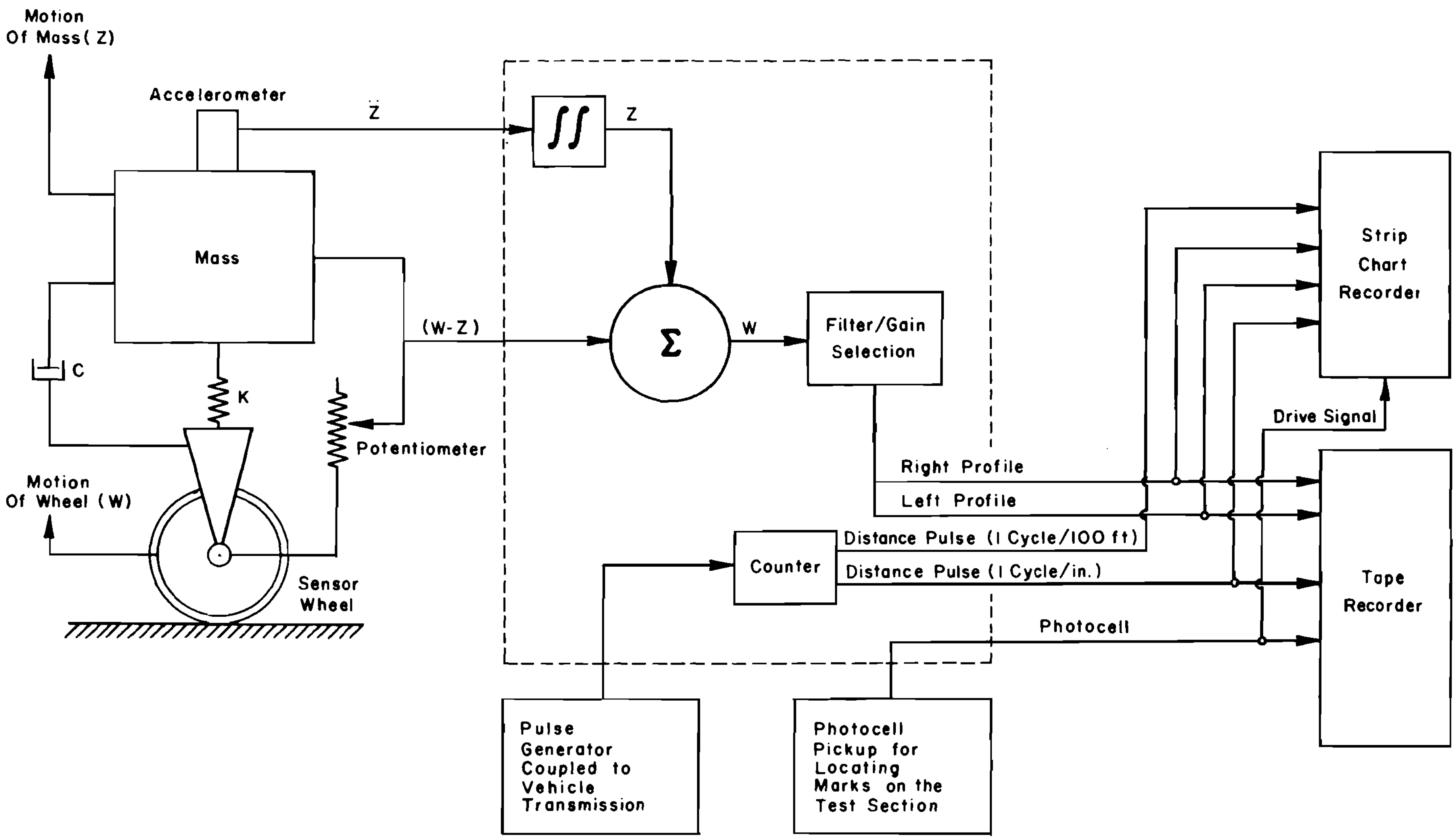


Fig 2.2. Detailed block diagram of measurement system. (continued on next page).

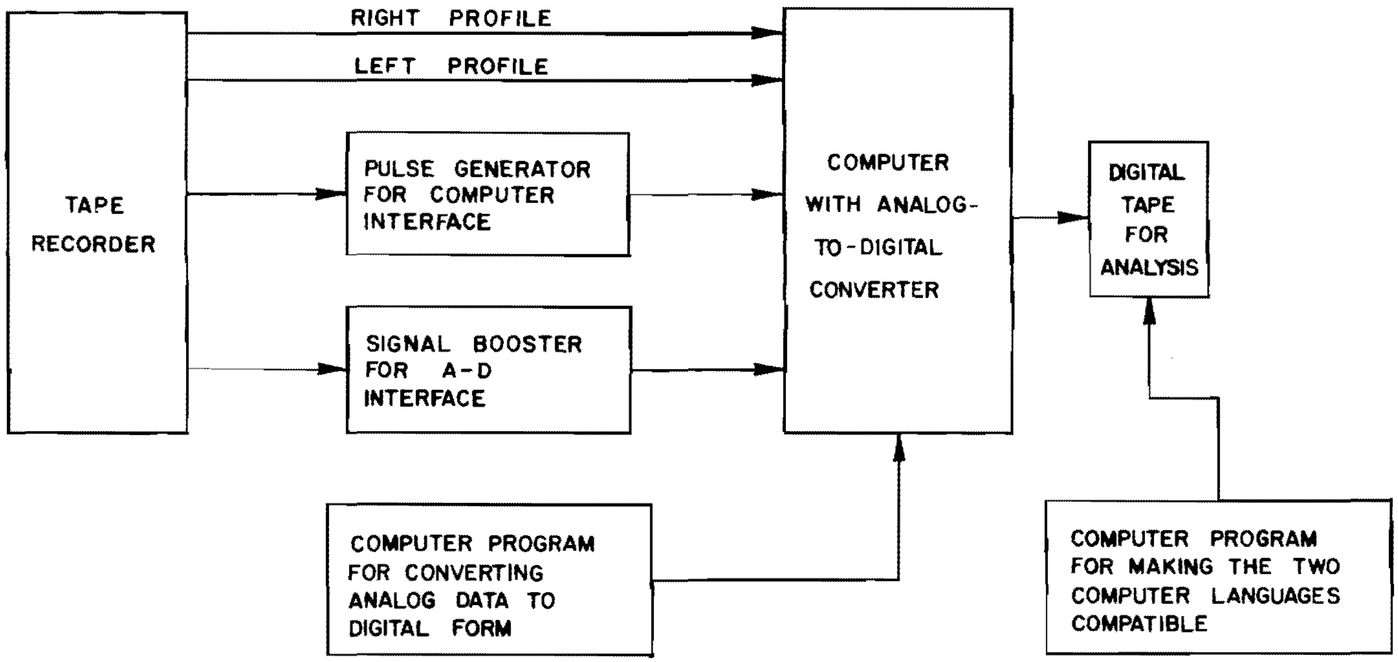


Fig 2.2. (continued from previous page).

Fig 2.3. Systron-Donner accelerometer.

Fig 2.4. Road-following wheel and assembly.

The road-following or sensor wheel is held in contact with the road surface by a spring-loaded arm as shown in Fig 2.4. Note also in Fig 2.4 that the potentiometer is mounted above the sensor wheel on the wheel support and is attached to the vehicle body directly above the sensor wheel. The trailing arm is free to rotate about the transverse and vertical axes; however, rotation about the transverse axis is constrained by a torsion bar spring. See Ref 2 for further details on the trailing arm. Raising or lowering of the trailing arm is accomplished hydraulically, by a hydraulic actuator and a pump driven by an electric motor.

The road-following or sensor wheel (see Fig 2.5) is specially constructed, with a high strength to weight ratio. The natural rubber tire is molded to the wheel rim, and the outside diameter is ground concentric with the wheel shaft. According to Law Engineering, for accurate measurement, the eccentricity of the wheel is considered excessive if it is over 0.005 inch. They report that road wear on this wheel was not considered to be a significant factor in early tests. Our experience has indicated, however, that road wear is a significant factor, as discussed in Chapter 4.

Road distance measurement is obtained with a Veeder Root Rotary Pulse Generator coupled to the vehicle's speedometer drive. Two hundred and fifty pulses are generated per revolution of the pulse generator, amounting to approximately 47.4 pulses per foot. A counter located in the profile computer reduces this value to approximately 11.84 pulses per foot. This value is recorded on magnetic tape for distance references and for synchronization with data sampling in the A-D process and hence distance identification. The counter also further reduces the 47.4 pulses per foot signal to a signal of one pulse for every one hundred feet on the pavement surface. The strip chart has an optional drive which can be run off a fixed time base or off the distance pulses for a direct distance scaling of the pavement surface.

Reference to the location of a particular point on the road is achieved through the use of a photocell sensing unit. A light source mounted under the vehicle is focused on the pavement. A photocell aimed at the pavement is then used to sense changes in pavement reflectivity, i.e., a white paint stripe on a dark pavement. Whenever such a change occurs the photocell induces a voltage proportional to this change which is amplified and used to open or close a relay. The relay changes are monitored for rapid visual display on the strip chart and are also recorded on the magnetic tape recorder. As indicated in

Fig 2.2, the right and left profile, the distance pulse or the sampling signal, and the photocell signal are all recorded on the magnetic tape recorder during the measuring process.

Two persons are required to operate the profilometer when making road measurements: a vehicle driver and an operator for the electronic equipment. In addition to the standard operating controls the driver is provided controls for warning lights, raising or lowering the trailing arms, and indicating specific events. The driver is also provided a visual and audio alarm system for indicating speed errors and computer overloading. The driver may record pertinent data such as test section information and filter-gain combinations on the voice channel of the Honeywell 8100 FM tape recorder. For maintaining constant speed, the vehicle has an automatic speed control system. The driver may monitor speed errors by a speed error meter in which variations in the speed selected in the profile computer by the operator may be observed. The meter is calibrated such that variations within ±5 mph of the selected speed result in full-scale meter deflections. The speed error meter is located on the left side of the driver's display panel as noted in Fig 2.6. An audio speed error alarm provided by the profile computer can also be used to indicate speed variations. The amount of speed variation is indicated by the intensity of the signal; i.e., the intensity of the audio signal decreases as the vehicle speed approaches the selected speed and increases in proportion to an increasing error.

The other meter shown in Fig 2.6 (right side) indicates the one hundred-foot distance intervals as denoted by full-scale changes in the meter pointer. Every one hundred feet of distance traveled by the profilometer vehicle results in full-scale changes in the meter reading. The red light located in the center of the display provides the driver visual indication of a computer overload condition.

Further information on the profilometer output signals is provided in the section on the profile computer subsystem (see also Ref 2).

Two independent power systems are included in the profilometer: the standard vehicle power system and an independent supply for the profilometer equipment. Alternating current is supplied to the electronic components by three inverters. A 250 va inverter supplies the profile computer. A 500 va inverter supplies the Honeywell recorder and the operator's control panel. A Powercon 250 va vibrator powers the Brush recorder and the Brush pulse generator.

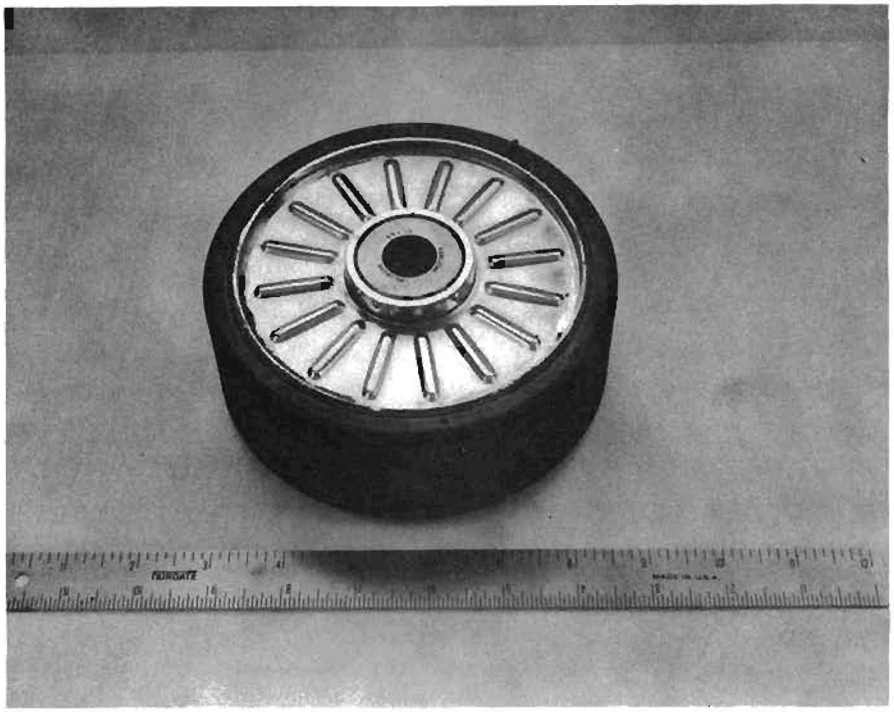


Fig 2.5. Sensor wheel.

Fig 2.6. Speed error indicator and 100-ft marker.

Profile Computer

The profile computer is shown in Fig 2.7. Figure 2.8 illustrates symbolically the profile computer subsystem. As noted in this figure, the computer has inputs from (1) body acceleration for both right and left sides of the vehicle, (2) sensor wheel and body displacement difference for both right and left sides of the vehicle, (3) distance traveled as denoted by pulses per foot, and (4) photocell sensing for location of marks on the test section. The computer then provides as outputs (1) the right and left road profile measurements, (2) distance traveled denoted by approximately one pulse per inch, (3) distance traveled denoted by one pulse per hundred feet, (4) a photocell sensing signal (logical), and (5) a speed error audio reference signal. There are three selectable parameters which affect the right and left profile measurement outputs. These are (1) high pass filter selection, (2) gain or measurement sensitivity selections, and (3) vehicle operating speed selection.

The four high pass filter selections are used for attenuating frequencies below 0.3, 0.6, 1.0, and 3.0 radians per second. The four gains of 0.2, 0.5, 1, and 2 volts/inch (vpi) are available for selecting profile gain sensitivity. As may be noted from the measuring sensors, the long wavelength profiles affect the vehicle body and thus are sensed primarily by the accelerometer. The short wavelength profiles such as bumps and potholes are sensed primarily by the traveling wheel (The vehicle suspension system dampens the effects of the high frequency small magnitude bumps). Since the magnitudes of the longer wavelengths vary considerably as noted from the varied elevations of hills, dips, etc., profile scaling, or gain selection, is necessary. By the use of the four filter selections, attenuation of the undesirable long wavelengths is possible. Since the measuring speed determines the frequency of the long wavelength components, judicious selection of a speed-filter and gain combination is required to make the best measurement of a particular section.

The six speed selections of 10, 20, 34, 40, 50, and 60 mph on the vehicle profile computer are used to provide the driver speed error display meter a reference so that adjustments of the vehicle cruise control can be made for the desired speed.

In considering the speed-filter-gain relationship from an electronic viewpoint, it should be noted that integration of DC or near DC signals by electronic integrators results in an unbounded output as time increases without bound. Thus, the four filters help maintain stability of the profile

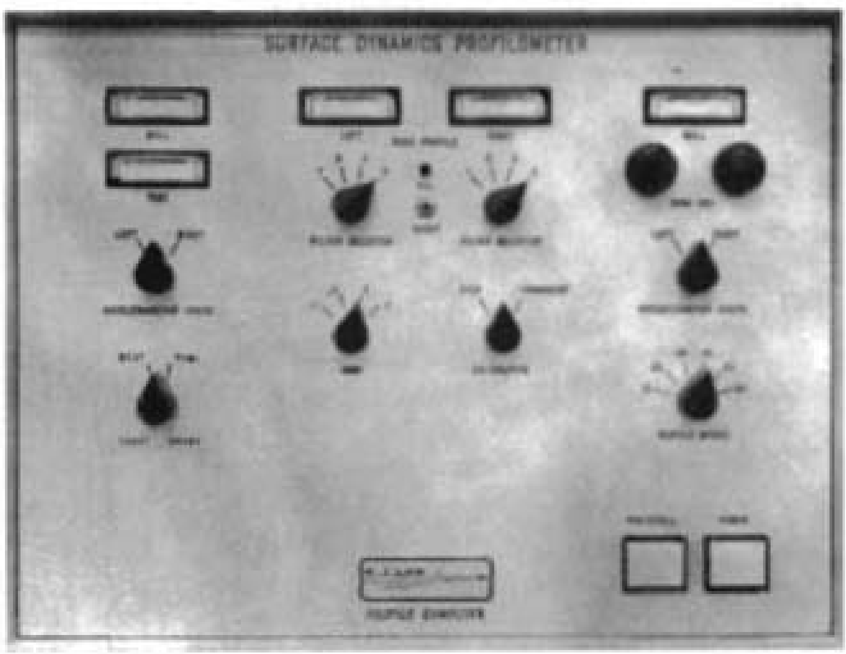


Fig 2.7. Profile computer.

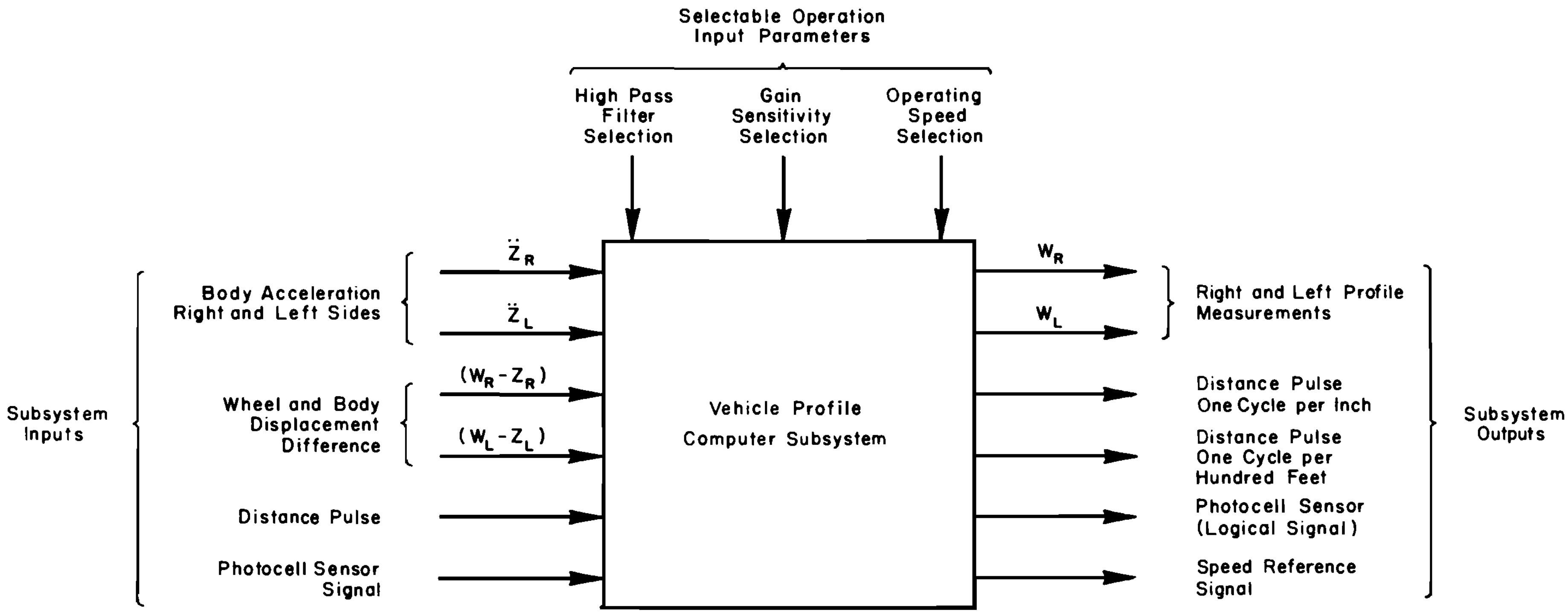


Fig 2.8. Profile computer subsystem.

computer by attenuating the long wavelengths. Even with these selections, however, low frequency profile components of sufficient duration and magnitude can saturate the integrator amplifiers. To prevent this occurrence, an overload circuit was designed which shorts the integrating capacitors and reinitializes the subsystem. Once this occurs, however, the profile signal obtained during this overload condition and for a few seconds thereafter is erroneous. Chapter 4, Systems Analysis, should be consulted for speed-filter-gain selection characteristics.

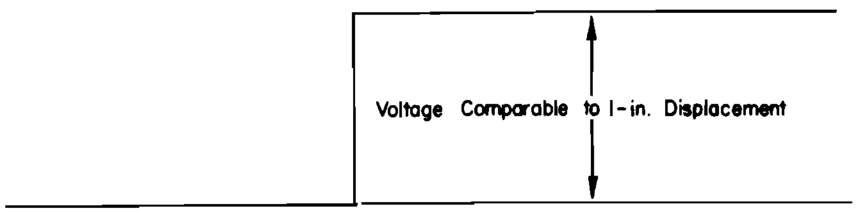
Two calibration signals are used by the analog computer subsystem for providing scaling and filter information. The voltage amplitude comparable to a continuous 1-inch-profile displacement (Fig 2.9) is obtained by a simple control switch on the front panel of the computer (Fig 2.7). Similarly, the free response of the system can be obtained by a transient switch (Fig 2.9) which when activated excites the system with a voltage pulse comparable to a 1-inch impulse displacement. The high pass filter selection can then be checked by noting the zero crossover point. When recording a one-inch step or transient, the vehicle is normally stationary and hence the distance pulse is zero. In order to provide a sampling signal for the A-D process and also a drive signal for the strip chart recorder, a constant 500 Hertz signal is provided to replace the distance pulse via a time-distance switch on the profile computer.

The frequency response of the profile computer is provided in Chapter 4, Systems Analysis.

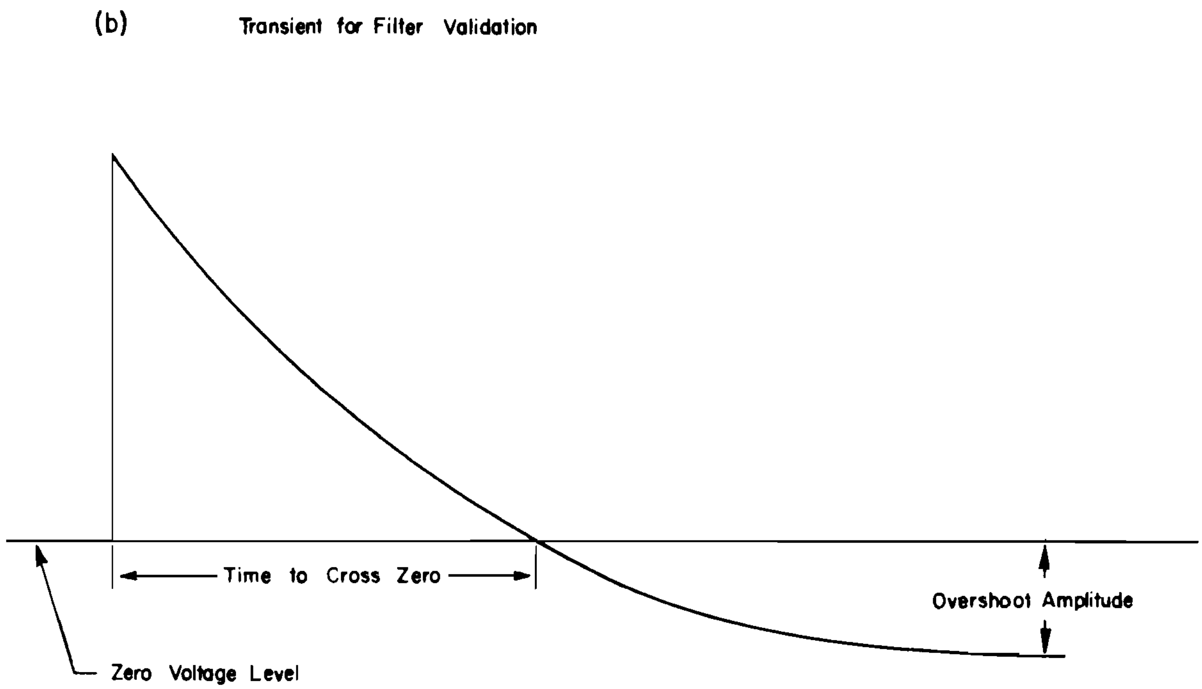
Recording Equipment

As indicated in Fig 2.2, a strip chart recorder and a magnetic tape recorder are used for recording the road profile information. The strip chart recorder provides an immediate permanent visual copy of the road profile. The magnetic tape record is used for subsequent analog processing or A-D processing.

Brush Mark 280 Recorder. The Brush Mark 280 recorder is a two-channel analog recorder with two event pens and pressure ink writing system providing 0.5 millivolt per chart division maximum sensitivity capability. The ±25 division chart (center zero) and sensitivity of 0.4 volt per division will record the full-scale ±10 volt output of the profile computer. With a X1.0 gain profile computer sensitivity selection, each chart division represents



(a) One-inch displacement for scaling data.



(b) Transient for filter validation.

Fig 2.9. Typical calibration signals.

0.4 inch of road profile displacement. Resolution at the X2.0 gain sensitivity selection is 0.2 inch. The two analog channels are used to display the right and left road profile measurements. The one hundred-foot distant pulses and the photocell sensing signal are displayed on the two-event channels. Pulses from the Veeder Root pulse generator trigger each step of the paper drive in the distance mode of operation.

The upper frequency response limitation of the Brush recorder should be noted. This recorder is flat to 35 hz for a 50 division peak-to-peak signal, 60 hz for a 25 division peak-to-peak signal, 100 hz for a 10 division peak-to-peak signal, and 200 hz for a 2.5 division peak-to-peak signal.

Honeywell 8100 Magnetic Tape Recorder. The Honeywell 8100 magnetic tape recorder is equipped with eight FM record/reproduce channels and four recording speeds. An FM compensation channel for playback compensation is provided as well as a voice monitor channel. As noted from Fig 2.2, four of the eight channels are used in the current system for recording right and left profile measurements, 1-inch distant pulses, and the photocell sensing signal. A fifth channel is used to record the system ground. The remaining three channels are then available for any additional requirements. The 3-3/4 inches per second recording speed is used to provide a frequency response from DC to 1.25 Khz. The voice channel is used for identifying section, speed-filter-gain selection, and calibration information.

The 42 db signal-to-noise ratio of this FM tape system allows eight-bit resolution of digitized data reproduced from the analog tape.

Analog-to-Digital Subsystem

General. The A-D subsystem is used to digitize the analog profile signals obtained by the profilometer into digital values for digital computer analysis. The digitizing process is accomplished with an SDS 930 general purpose computing facility. Figure 2.2 illustrates the A-D subsystem. As indicated in this figure, the A-D process is dependent on four major subsystems, the Honeywell 8100 analog tape deck for data playback, an HP 214A pulse generator, a photocell signal booster unit, an SDS 930 computer facility with an A-D peripheral unit, and an A-D program (See Fig 2.10).

As indicated in this figure the right and left profile signals are digitized into 12-bit (11 bits plus sign) data words in accordance with the distance or sampling signal. The HP 214A pulse generator is used to interface

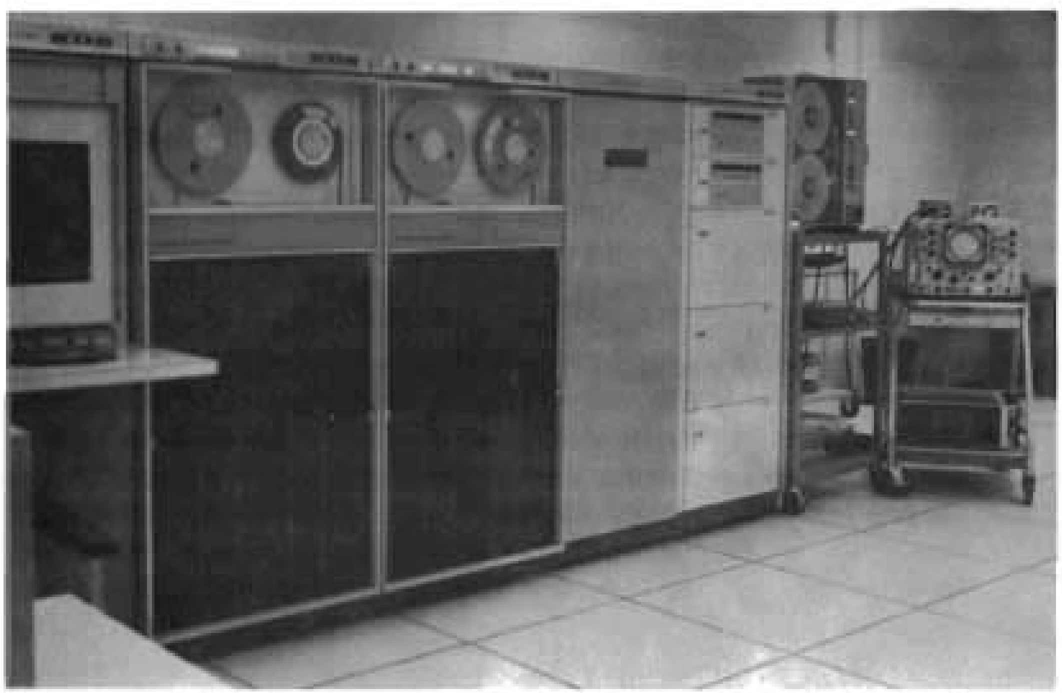


Fig 2.10. SDS 930 computer console and equipment hookup for A-D processing.

the sampling signal with the SDS 930 computer. The photocell signal booster unit interfaces the photocell signal with the SDS 930 facility. The digitized 12-bit data words are then written on standard digital tape in 1500-word blocks at 556 bits per inch.

Analog-to-Digital Process. Figure 2.11 expresses symbolically the A-D subsystem and illustrates the four primary signal inputs to the A-D subsystem. Both the photocell sensing signal and the begin/end conversion signal are necessary to begin the A-D process. As noted in the figure, the begin/end conversion signal comes on first, initializing the system. The program then waits until the photocell signal is sensed which indicates the beginning of the section to be measured and hence the beginning of the conversion process. If the photocell signal is not used, A-D operations are controlled by the begin/end conversion signal. The conversion process then continues in accordance with the sampling signal until the begin/end conversion signal drops, indicating the end of the conversion process and thus the end of the digitized data file. The begin/end conversion signal is initiated and terminated manually upon command from the profilometer operator via the voice channels on the Honeywell recorder.

As the analog data are digitized, they are stored in 1500-word blocks after which they are written on digital magnetic tape at 556 bpi. Thus, two memory buffers are used by the computer, one for inputting the digitized values and the other for outputting the data on the digital tape. Upon receipt of the end of conversion signal, a five-word identification record followed by an end of file is written signifying the end of the conversion process and hence the data file.

The current A-D subsystem has the following capabilities:

(1) sample resolution of 11 bits plus a sign bit,

(2) up to eight channels of simultaneous sampling at rates up to 16/N Khz per channel where N is the number of channels,

(3) sampling rate may be externally driven at any external rate or reduced multiple of this rate, i.e., sampling rate equals external rate W, where W is any positive integer from 1 to 2,048. For example, with a 2 Khz external sampling signal and W = 4, the sampling rate will be 2 Khz/r or 500 hz,

(4) sample rate may be internally controlled by the HP 214A pulse generator, and

(5) the conversion process may be controlled by the photocell signal and the begin/end conversion signal or simply the begin/end conversion signal.

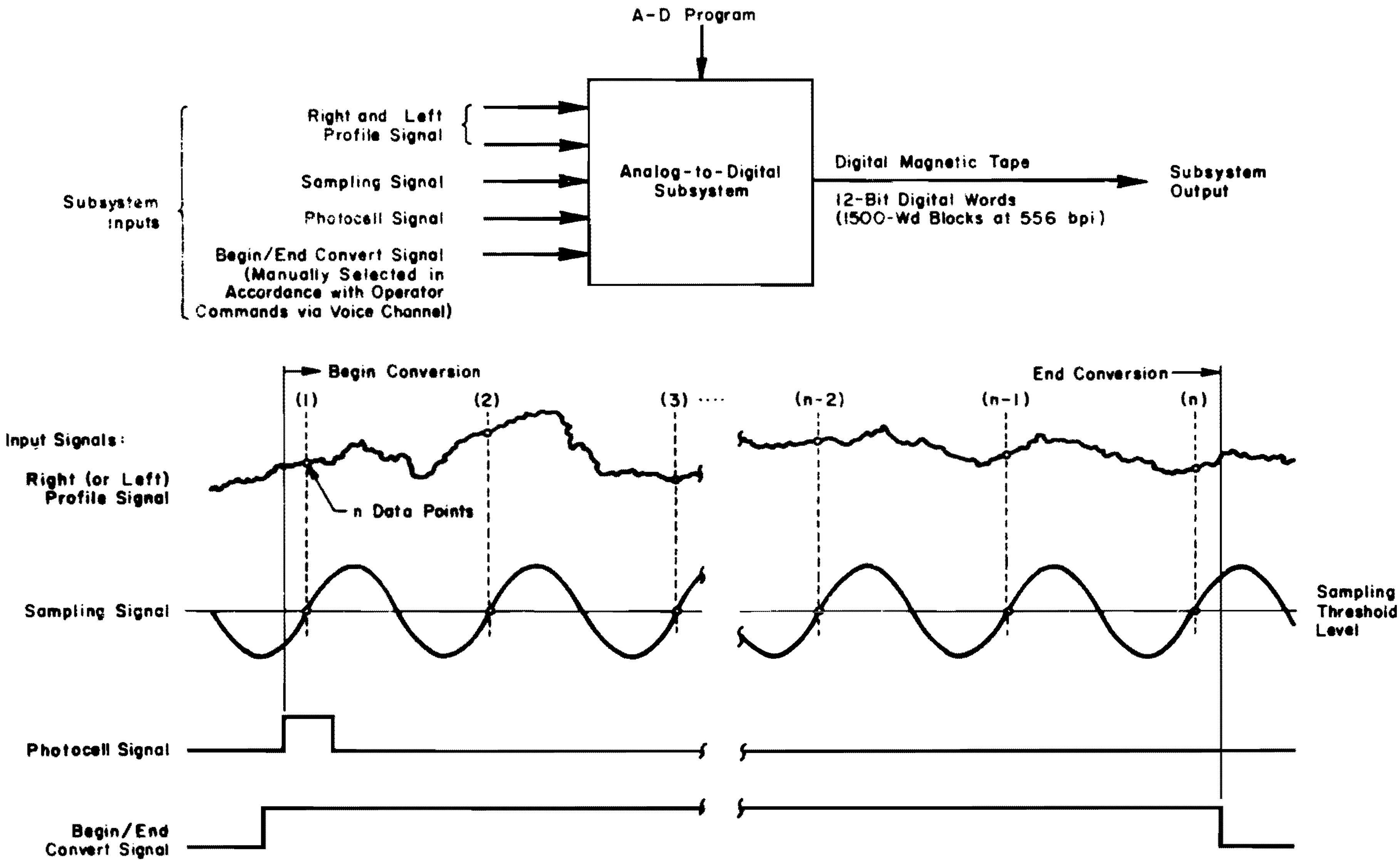


Fig 2.11. Analog-to-digital subsystem with inputs.

A-D Program

Figure 2.12 depicts a general flow chart of the A-D program (See Appendix 2 for the source program listing). Both Fortran and Symbolic languages are used in this program. Briefly, the general flow depicted in Fig 2.12 is as follows:

(1) The program is loaded and various operation parameters are entered by the operator, such as

(a) New or old data tape: e.g., if the tape is not a new data tape, the last data file or any other desired file is located and the tape is positioned to begin after that file.

(b) Automatic or manual control mode: e.g., if a conversion process is desired for beginning and ending the conversion process solely by a series of control signals and thus without entering any new file identification information, the automatic control mode is selected.

(c) If the photocell signal is to be ignored: i.e., the conversion process will be initiated and terminated solely by the begin/end convert signal.

(2) The program waits for a command of some nature, such as the begin conversion and/or photocell signal for initiating the A-D process.

(3) The program uses two 1500-word buffer areas so that while one buffer is being filled by the A-D input operations, the other buffer will be emptying on the magnetic tape.

(4) After 1500 words have been read, a new read command is immediately initiated to insure the required sampling rate is maintained.

(5) The 1500 12-bit words in Buffer 1 are written in binary on the magnetic tape.

(6) This procedure is repeated, i.e., filling and emptying of alternate buffers from the A-D unit to the magnetic tape, until the end of the analog record or section being measured is detected.

(7) When the analog record has been completed, the conversion process is terminated by the sensing of the begin/end conversion signal. A five-word identification record is then written at the end of the last data record. If the next analog record is to be read soon after the end of the last record and no additional identification information is desired, the program automatically increments the data file number and waits for the next begin conversion command(s), i.e., the automatic control mode was specified. If not, or if other identification is required, the program stops and waits for further information or commands from the operator.

(8) Each data set (data records plus identification record) is separated by an end of file. Two end of files are written at the end of the last data set on the magnetic tape.

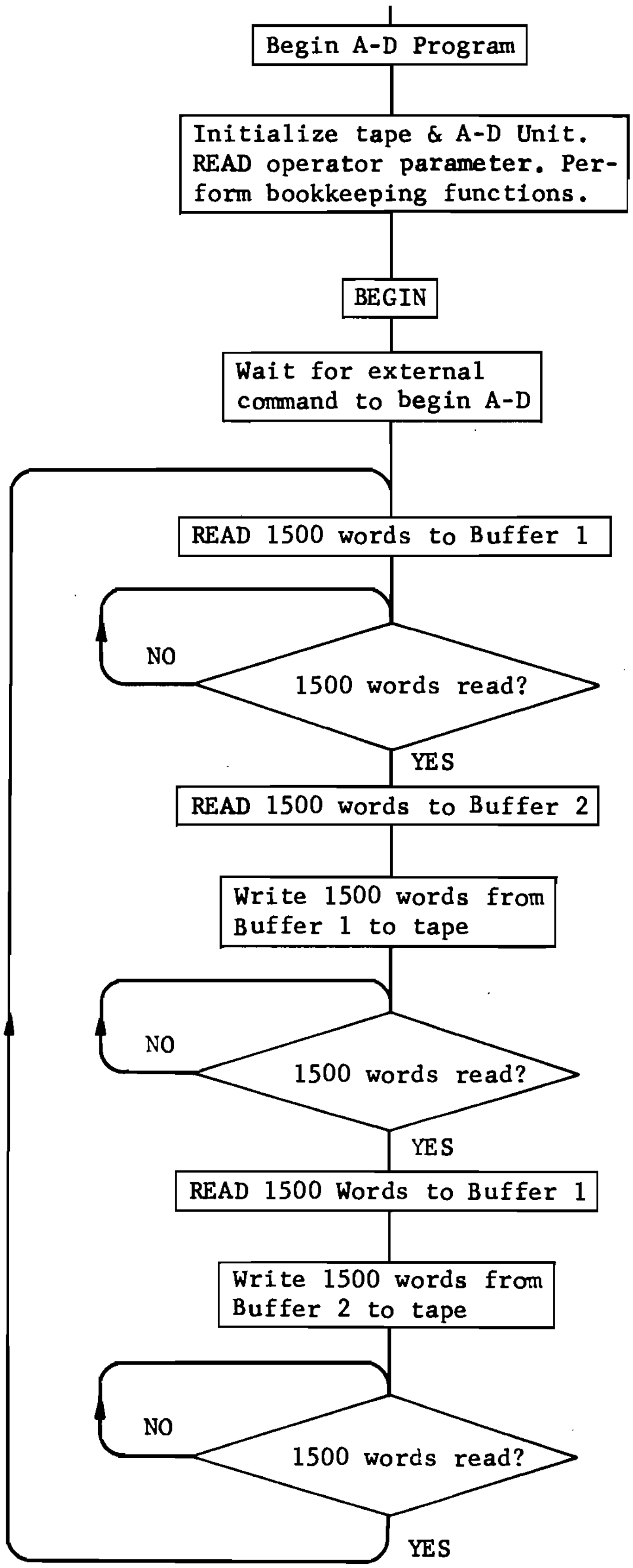


Fig 2.12. Analog-to-digital program for SDS computer (continued on next page).

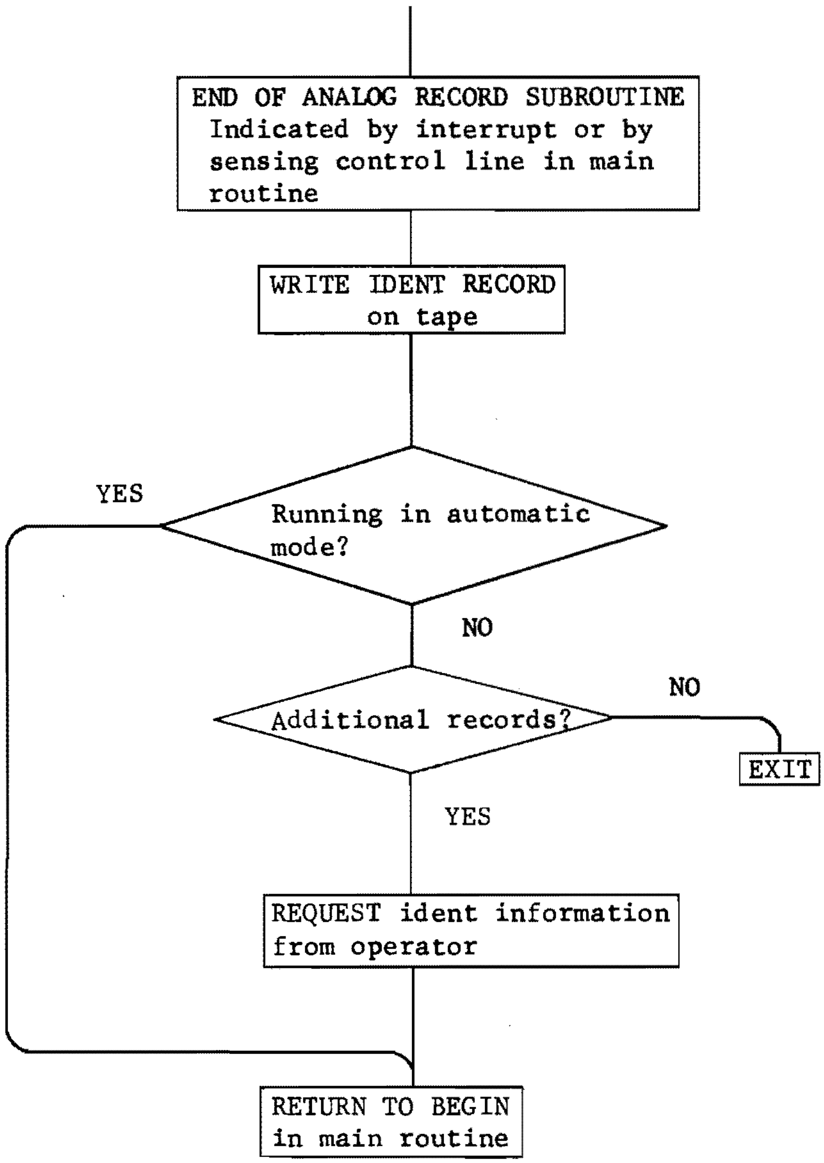


Fig 2.12. (Continued from previous page).

Each digitized data file is formatted in accordance with Fig 2.13. As shown in this figure, each data set or file is accompanied with an identification record generated during the A-D process. This identification record includes

(1) a data file number which is used by the program for identification and also positioning of the data tape when, for example, adding, replacing, or deleting additional data files,

(2) the number of converted 1500-word records in the data file,

(3) the number of converted data words in the last record,

(4) the total number of conversions in the data file, and

(5) a 24-bit identification tag for additional operational information, such as filter-speed-gain selection and date.

CDC 6600

After the profile data have been digitized and written at 556 bpi on a digital tape by the SDS computer, the data must then undergo a transformation to make it compatible to the computer which performs the data analysis. Since current data analysis is performed on a Control Data Corporation (CDC) 6600 at The University of Texas, the necessary transformation changes the SDS profile data into data compatible with the CDC 6600 data analysis programs. The compatibility changes can be made either on the SDS 930 or the CDC 6600. The compatibility program currently used is run on the CDC 6600. To transform the SDS binary data words into CDC 6600 binary data, this program does the following:

(1) Examines the data for possible parity errors. Because of the analog tape recorder, a continuous conversion process from beginning to end of a road section is required. Consequently, time is not available during the digitizing process for checking for bad digital tape writes. Thus, when the digital tape is read parity errors are possible. In statistical analysis of large samples of data, the effects of these errors may vary (particularly if errors are omitted or replaced by approximations), hence the importance of identifying the locations and numbers of these errors is realized. By the use of high quality digital tape, parity problems are alleviated. High quality tapes are used in the digitizing process and consequently to date no such problems have occurred.

(2) Reverses the order of each set of five 12-bit words from one to five to five to one. This word order change is necessary because of the characteristics of the CDC data channel and the SDS binary write operations.

(3) Changes the 12-bit SDS binary words into 60-bit CDC binary words.

(4) Changes each binary word from the two's complement mode as used in the SDS machine to a one's complement mode as used by the CDC machine.

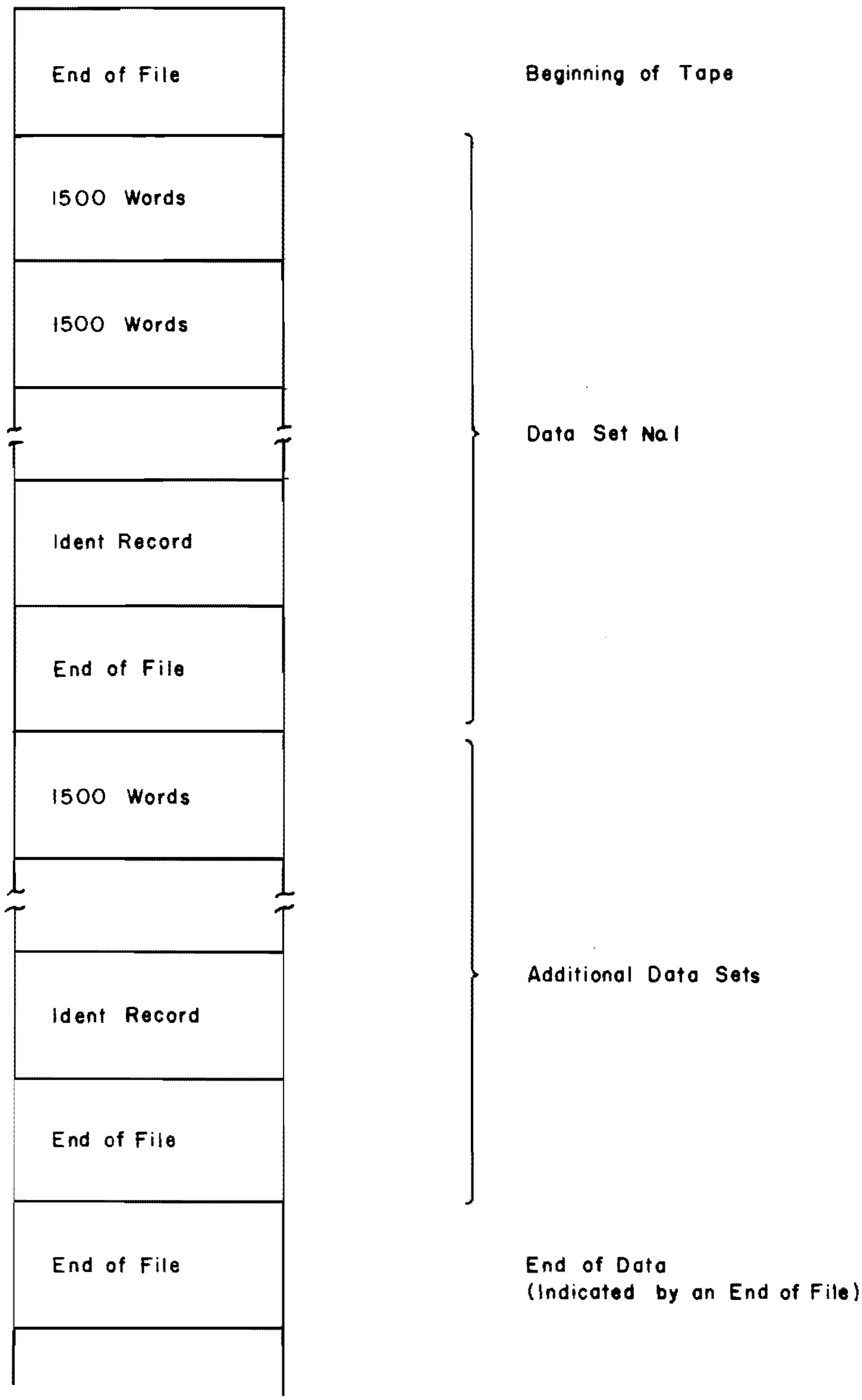


Fig 2.13. Simulated data array on digital magnetic tape.

CHAPTER 3. OPERATING PROCEDURES

This chapter describes the general operating procedures used when making a typical road profile measurement run and may be used as an operator's guide. The chapter is divided into two parts - the operating procedures for taking the data with the profilometer, and procedures used in digitizing the data with the analog-to-digital converter. Also included within the operating procedures for the profilometer is a discussion on speed-filter-gain selection criteria.

GENERAL OPERATING PROCEDURES (SD PROFILOMETER)

The operating procedures for setting up the profilometer and making a typical data run are as follows:

1. Visually inspect the profilometer. Examine the potentiometer mounting on the torsion bar arm to insure this mounting is proper or has not been broken.
2. Start vehicle engine.
3. Set engine idle for a tachometer reading of no less than 1200 rpm maximum.
4. Turn on main system power.
5. Turn on profile computer, Brush strip chart recorder, and Honeywell tape recorder (allow 20 minutes warm-up period).
6. Turn on the digital voltmeter and variable DC power supply. (Recommended test equipment - not furnished as part of the original profilometer system.)
7. Select 3-3/4 ips recording speed and thread tape on recorder.
8. Calibrate Honeywell recorder in accordance with the Honeywell 8100 Portable Recorder/Reproducer Instruction Manual using the variable DC power supply and digital voltmeter for the necessary external voltage requirement. Table 3.1 provides the voltage calibration values for the profile, sampling, and photocell channels.
9. Calibrate profile computer as follows (Item numbers referred to are shown in Fig 3.1).

TABLE 3.1. CHANNEL CALIBRATION VOLTAGE VALUES

Channel	Function	Calibration Voltage
1	Right Profile	±3.0 volts
2	Left Profile	±3.0 volts
5	Sampling Signal	±6.25 volts
6	Photocell Signal	±4.0 volts

a. Power Supply*

(1) Measure between Pin X and ground Pin Z on any of the cards.

(2) If voltage is not -15 + .010 vdc, adjust power supply module for -15 vdc (adjustments are located on each side of the Acopian power supply module).

(3) Repeat above for +15 vdc and Pins Y and Z .

NOTE: Most of the following adjustments are dependent upon proper power supply voltages.

b. Potentiometer (Cards J3 and J15)

(1) Potentiometer Check

(a) Lower the road-following wheels to the ground by depressing LOWER on the operator's control panel. Check to insure that the wheels are lowered properly.

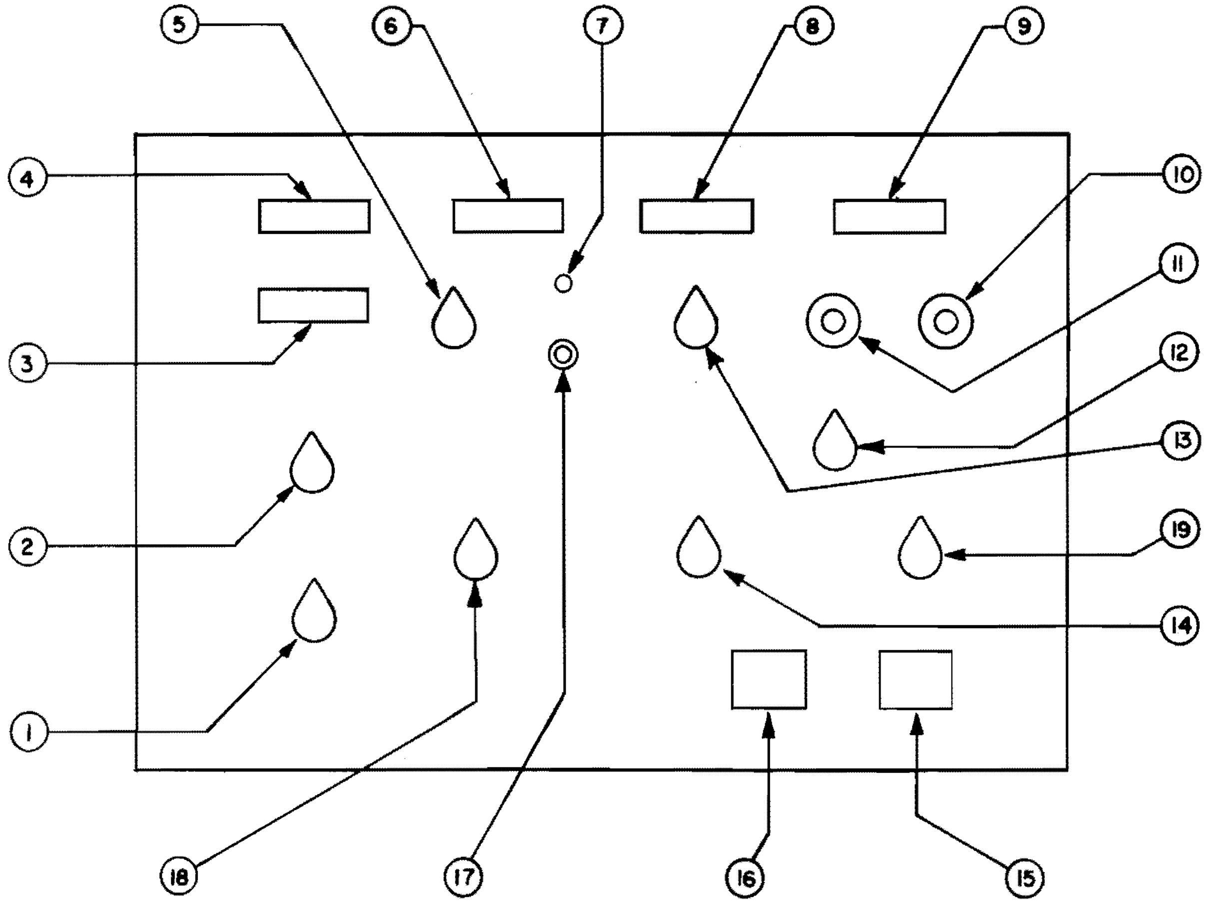
(b) Monitor the potentiometer amplifier output by rotating the potentiometer test switch to the right (Item 12).

(c) Null the potentiometer signal by means of the bias adjustment and lock this setting (Item 10).

(d) Repeat (b) and (c) above for the left potentiometer (Items 11 and 12).

(2) Transient Response Check

*Any movement of the vehicle will cause a change in the potentiometer and accelerometer outputs and hence a corresponding change in the amplifier output; therefore, the vehicle must remain stationary during calibration.



Legend

1 Time/Distance Selector

2 Accelerometer Bias Check

3 Accelerometer Bias Meter

4 Accelerometer Null Meter

5 Left Filter Selector

6 Left Profile Output Voltage

7 Overload Indicator

8 Right Profile Output Voltage

9 Potentiometer Null Meter

10 Right Potentiometer Bias Adjustment

11 Left Potentiometer Bias Adjustment

12 Potentiometer Bias Check

13 Right Filter Selector

14 Calibration Switch (Step, Transient)

15 Power Switch

16 Photocell Switch

17 Reset Switch

18 Gain Selector

19 Vehicle Speed Selector

Fig 3.1. Profile computer.

(a) Select the desired filter channel (Items 5 and 11).

(b) Set the gain switch to 1 (Item 18).

(c) Switch chart recorder drive selector switch to time (Item 1).

(d) Set chart drive speed to 20 mm/sec x 1.

(e) Rotate calibration switch to transient position and hold until transient dies out (Item 14).

(f) Observe that the peak deflection is approximately five major divisions and that the time to zero crossover corresponds to the time required for the filter selected (Fig 2.9).

(3) Step Response Check

(a) Rotate the calibration switch to the step position (Item 14).

(b) Observe a step change in profile output of five major divisions (Fig 2.9).

(4) Potentiometer Isolation Amplifier

(a) Remove the four screws holding the potentiometer cover* plate to the potentiometer support.

(b) Insert 1-inch blocks between the cover plate and potentiometer support member extending the potentiometer by 1 inch.

(c) If output is not 1 ± .005 vdc, adjust amplified gain R23 for 1 vdc and repeat above.

(d) Replace screws in cover plate, then repeat for the other potentiometer.

c. Accelerometer Cards (J3 and J15)

(1) Accelerometer Check

(a) Apply a 1 ma test current to the right accelerometer by means of the spring return selector switch.

(b) Observe that the null meter remains centered.

(c) Repeat for the left accelerometer.

(2) Short the accelerometer input isolation amplified A1 to ground (Pin N to Pin Z) and adjust R5 for zero output as read from TP2 and TP3 (ground). If the zero condition

*Items 4(a) and (b) may also be accomplished by use of the 1-inch step switch (Item 14, Fig 3.1).

cannot be obtained solely by R5, adjust R12 as necessary. (When completed remove shorting wire.)

(3) Accelerometer Isolation Amplifier

(a) While monitoring accelerometer output (TP2) on Card 3 for right and Card 15 for left, adjust R12 for ± 10 mv DC or less.

(b) Depress bias control switch located adjacent to card rack.

(c) If the accelerometer amplifier output does not change by 5.791 ± .020 vdc adjust gain R10 for 5.791 vdc.

d. Profile Computer Amplifiers (Cards J1 and J13)

To balance the profile computer amplifiers, the right (left) amplifier card is removed and placed in slot J20*. With the profile computer amplifier card in this slot, the input to the amplifier string is grounded. On top of the amplifier card are located the outputs (TP1 through TP5) of each amplifier in the string. Once the amplifiers have had about 20 minutes of warmup time, the appropriate variable resistor is adjusted to yield a zero voltage output (± 0.01 mv) between each test point and ground. The appropriate resistor for each amplifier is as follows:

Amplifier	Resistor	Test Point
A1	R1	TP1
A2	R3	TP2
A3	R5	TP3
A4	R11	TP4
A5	R15	TP5

e. Buffer Amplifier (Card J19)

To align the buffer amplifier, the input to the buffer amplifier is shorted to ground (Pin J then U to Pin Z). Then adjust R2 for zero volts (± 10 mv) between TPR (TPL) and TOC. Repeat for R1.

10. Turn photocell lamp on.

11. Switch desired filter and speed combination.

12. Estimate gain selection and set in computer.

13. Calibrate Brush recorder in accordance with Brush Mark 280 Operating Instruction Manual.

---

*Turn power off when removing cards.

14. Select 5 mm/inch recorder sensitivity for monitoring profile data run.

15. Turn on warning lights.

16. Make test pass over the section of interest to determine*

    a. If the speed control locks in properly at desired speed.

    b. If the gain selected is at the proper value by observing the Brush recorder to see if the profile data remain on the chart.

    c. If the photocell senses the section marker by observing the photocell relay closures on the Brush recorder. Adjust the photocell sensitivity on Card 7 in the profile computer if the section marker is not sensed properly. Oversensitivity is indicated from oversensing pavement reflectivity changes, i.e., signals are generated even with no section markers. Undersensitivity may be noted if the markers are not sensed at all. In some instances it may be necessary to repaint the section marker if a proper photocell sensitivity gain cannot be found.

    d. If a sufficient distance is allowed for accelerating the vehicle preceeding the run. This allows time for transients introduced by vehicle accelerations to dampen before entering the test section. The minimum distance d is a function of filter selection ω and vehicle speed s or

$$d_{min} = \frac{10s}{\omega}$$

where

s is in mps

and

ω is in rad/sec

17. Make recording on Brush and Honeywell recorders of 1-inch calibration step and transient.

18. The Brush recorder should be set for distance drive and the tape recorder started prior to entering the test section to insure that the tape speed has reached the proper level.

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*There are three rules which must be observed during all operations to prevent damage to the road-following assembly:

1. DO NOT make sharp or U-turns with the road-following wheels on the ground.

2. DO NOT back up with the road-following wheels on the ground.

3. The driver should observe the road so that the road-following wheels do not pass over ruts or longitudinal faults in the road that may force the road-following assembly to move transversely or pass over deep chuck holes which may damage the wheels.

19. The driver should then accelerate as smoothly and gradually as possible to the selected speed and maintain that speed as closely as possible while using a minimum of steering correction to maintain a straight path. When measuring a section with grade changes, it may be necessary for the driver to maintain speed control manually.
20. At the conclusion of the run, the driver should raise the road-following wheels while the operator stops the tape recorder and strip chart recorder.
21. Make duplicate test runs as required until 16a through 16d (above) are satisfied.
22. Run the profilometer over the road section using the Brush and Honeywell recorders to obtain road profile measurements. The voice channel on the Honeywell recorder should be used to identify the section and provide the necessary command information for the analog-to-digital process.
23. Bring the analog data tape back into laboratory for A-D processing.

FILTER-SPEED-GAIN SELECTION CRITERIA

The filter and speed selection used in measurement of a road profile effectively fixes the profile wavelengths that will be measured. The response curves of Chapter 4 denote the gamut of frequencies in which the system introduces no attenuation or phase shifts. Speed and wavelength are related to these frequencies by the following equation:

$$\lambda = \frac{V}{f} \tag{1}$$

where

λ = wavelength in ft,

V = velocity in ft/sec,

f = frequency in Hertz.

To determine a speed-filter combination for measurement of a road profile, first determine which profile wavelength measurements are wanted. Figure 3.2 provides a graph in which a given range of wavelengths can be used to obtain the proper filter-speed combination for phase shifts of 10 and 135 degrees (0.7 or 3 db attenuation).

For example, suppose one is interested only in those wavelengths smaller than 10 feet with no phase shifts exceeding 10 degrees. From the graph in

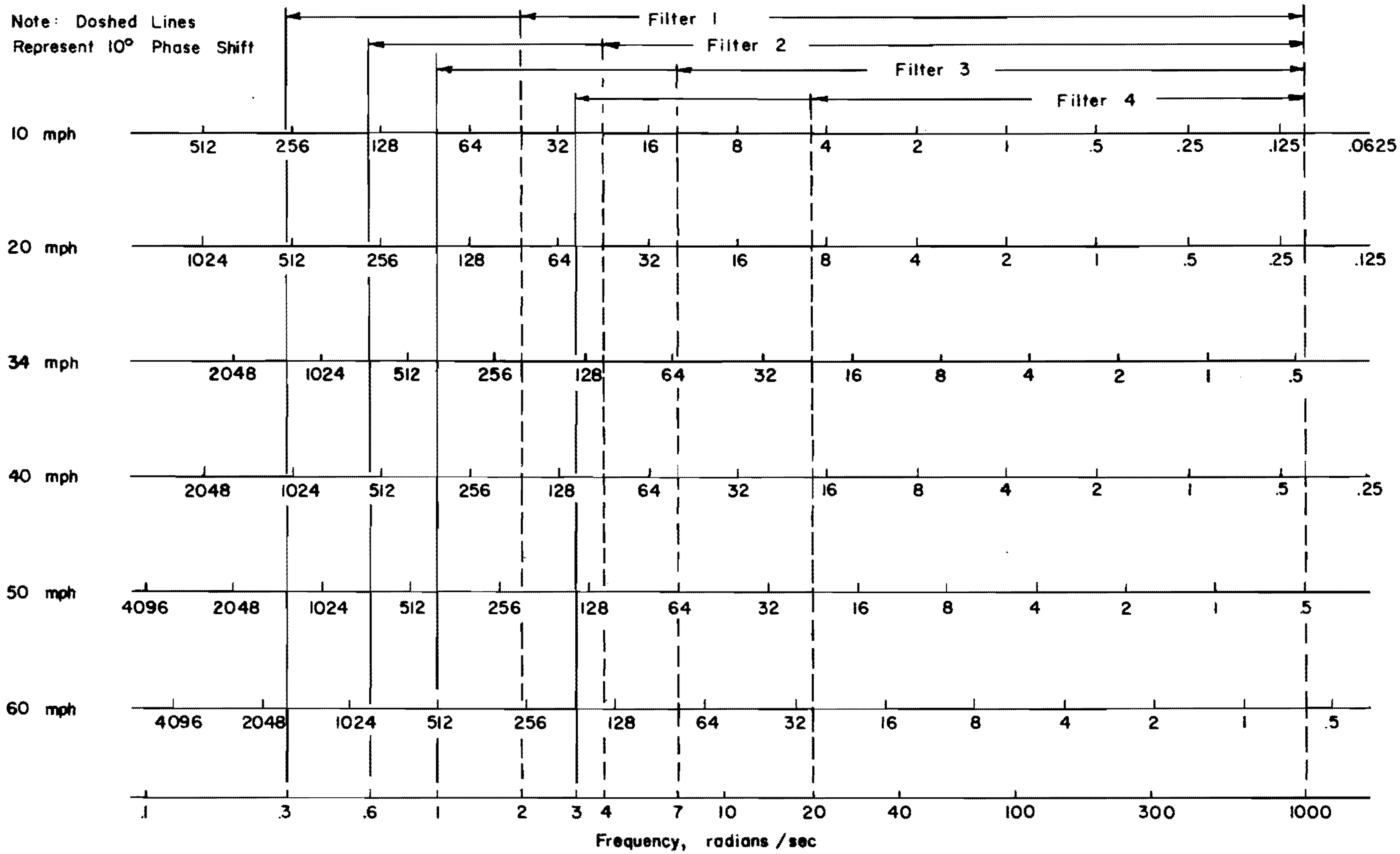

Fig 3.2. Filter-speed-wavelength selection graph.

Fig 3.2, it is observed that filter-speed selections of Filter 3 at 10 mph, or Filter 4 for the remaining speeds of 20 to 60 mph, can be used.

In a similar manner, one can begin with a given speed or filter and thus find the necessary combinations in accordance with Eq 1 and the system frequency constraints of Chapter 4 by use of Fig 3.2.

Four gain selections are provided by the profile computer for profile data sealing. The profile computer is designed for a voltage operation of ±10 volts. Voltage amplitudes exceeding this 10-volt range overload the computer and result in erroneous data. For a given data run, maximum resolution is obtained when the profile voltage amplitudes are as large as possible, i.e., when the voltage deflections near the ±10 volt capability of the computer. On the other hand, one must be careful not to exceed the ±10-volt range of the computer or the entire data run can be jeopardized. (Since the accelerometer and thus the voltage output changes are quite sensitive to speed variations the ±10-volt critical magnitude can easily be violated if the full-scale reading is too close to this ±10-volt critical magnitude.) It has, however, been found that the added resolution obtained by working with values near full-scale as opposed to those near say 2 volts is much greater than needed for measuring road profile. For instance, using 2 volts as full-scale and a gain of .2 (i.e., .5 inch = 1 volt) the voltage amplitude corresponding to a 0.1-inch profile change is 0.2 volt, well within the resolving capabilities of the system. With the gain of +2 this resolution drops to 0.02 volt for a 0.1-inch deflection which is marginal. However, the gain of 2 would not normally be used when deflections of this magnitude are desired.

In consideration of overload and resolution characteristics, the typical setup procedure is to calibrate the Honeywell recorder for ±2.5 volts and set the Brush recorder for 2-volt full-scale readings. Then before measuring a particular road section, a trial run(s) is made to establish a gain in which the profile voltage changes remain just within the ±2-volt Brush recorder readings. Then, if during the data run the voltage amplitudes should exceed the ±2-volt range, the magnitude is still within the limits of the Honeywell recorder and is also well within the limits of the profile computer. This calibration technique was ascertained through operating experience and has been found to be acceptable for most road sections. It should be noted, however, that this procedure can fail for some road characteristics. In such situations, the recorder calibrations should be reduced as needed, consistent with the constraint of the ±10-volt computer overload and the frequency response characteristics discussed in Chapter 4.

ANALOG-TO-DIGITAL OPERATING PROCEDURES

The following equipment is required for the analog-to-digital operation with the SDS 930 System:

1. Honeywell 8100 tape recorder
2. Patch box (patch network for interchanging recorder output channels to A-D input channels, SKS sense lines, and computer interrupt lines)
3. Hewlett-Packard 210 pulse generator
4. Logic booster
5. SDS 930 computer facility

   a. Connect the patch box to the tape recorder with tape input plug. Connect the analog input channels and SKS sense lines into the A-D input. Wire patch box such that Channels 1 and 2 (right and left profile) of the tape recorder are connected to A-D Channels 1 and 2. Channel 5 of the recorder (sampling signal) goes to the H-P pulse generator, Channel 6 (photocell signal) goes through the logic booster box to the SKS line 1. A small toggle switch is connected across the SKS line 1 and ground for manually overriding the photocell signal. The other SKS input (line 0) is connected to the manual begin/end convert switch.

   b. Attach the pulse generator output line to the computer interrupt input. Insure pulse generator is set for external trigger, pulse output at positive level, pulse amplitude at approximately 8 volts, and pulse width at about 5 microseconds.

   c. Connect photocell signal output from patch box to logic level box. Connect photocell override switch between logic booster box output and SKS input line 1. Second switch is attached directly to SKS input line 0.

   d. Turn on tape recorder and calibrate playback controls in accordance with Honeywell instruction manual. Set playback Channels 1 and 2 for 1 volt gain. Set Channel 5 playback gain control to midposition for interrupt input. Set Channel 6 playback gain to maximum value. Insure tape heads are clean.

   e. Place binary paper tape A-D program in paper tape reader. Place data tape on tape unit setting tape position selector to Channel 1 and tape density to 556 bpi.

   f. Turn on pulse generator and logic booster box.

   g. Load A-D program.

h. Make the following operator parameter assignments:

(1) Enter 1 for SKS Line 1 Parameter

(2) Enter 2 for Number of Conversion Channels

(3) Enter 1 for Interrupt Cycle Count

(4) Enter 0 or -1 for File Number depending on if new data tape or old tape

i. Perform A-D operation entering proper file number and identification information.

CHAPTER 4. ANALYSIS OF THE SYSTEM

GENERAL

This chapter describes the various system analysis techniques employed to determine the authenticity of the data obtained by the profile measuring system. It is divided basically into five parts: system analysis procedures, redigitization, scale factor sensitivity, system frequency response, and sensor wheel analysis. The first of these parts describes the procedures used to insure the validity of the profile data at the various stages in the data measuring flow path. The procedure described was instrumental in the development of the total measuring system and is currently used for isolating equipment problems or failures.

The measuring process includes A-D conversion of the profile data; thus, the digitizing process was examined closely to determine if any significant errors are introduced that could lead to misleading or erroneous road profile measurements. An experiment which was conducted to establish the significance of any such errors is described below.

To examine the sensitivity of the measuring subsystem to typical environmental conditions such as weather and operating techniques, an experiment to determine the sensitivity of the major electronic components of the profile computer to typical changes in the operating environment was conducted. This experiment is described below.

Since the measuring system has diverse effects on various frequencies in the road profile, it is important to establish the system frequency response in order to know how to evaluate this effect on various frequencies. The fourth section describes the response of the total system to various frequencies of input data. The final section provides some useful comments on the sensor wheel.

SYSTEM ANALYSIS PROCEDURE

Because of the size and complexity of the profile measuring system, a systematic procedure was programmed for use in early detection of system failures and to aid in the initial system development. Basically, this analysis procedure simply identifies the most likely failure areas and introduces the facilities available for the rapid detection of such failures. A typical example of the need for such a procedure would be the early detection of a noisy channel in the analog recording unit which could lead to misleading results when the road profile data are being analyzed.

The systematic procedure developed for system analysis is expressed symbolically in Fig 4.1. To formulate the system test procedure, check points along the system data flow path were selected where subsystem failure could affect the measurements process. Thus, each check point can be used to verify the system operation to that point. The entire test procedure should be followed as standard operating practice to insure satisfactory system operation. If a failure occurs, the test procedure can also be used as a guide for isolating the problem cause.

Briefly, the procedure described in Fig 4.1 is as follows:

(1) The potentiometer mounts and wheel assembly should be examined for possible breakage. The raise/lower cycle should then be checked to insure the wheels are raised, lowered, and latched properly. An inoperative road-following wheel will give erroneous profile data or introduce considerable noise in the data.

(2) The potentiometer and accelerometer can be tested for proper bias and operation by using the proper test switches provided on the profile computer. A failure in either potentiometer or accelerometer can result in erroneous data, frequent computer overloads, or considerable noise in the data.

(3) Operation of the profile computer is verified by balancing the operational amplifiers. The filters are tested by observing the transients either on the oscilloscope or strip chart recorder. Erroneous profile data or noise can be introduced by a malfunctioning profile computer.

(4) The Honeywell 8100 analog tape recorder should be calibrated to insure proper recording. An inoperative recorder can result in the complete omission of a channel or introduce noise in the data.

(5) The strip chart recorder should be calibrated. Once this recorder is set up properly, it can be used for continuously checking the operation of the measuring process.

(6) A test run of the vehicle with the use of the strip chart recorder will validate the operation of the photocell, the time/distance pulse, the 100-foot event marker and the right and left profile data.

(7) The Honeywell recorder should periodically be played back via both the strip chart recorder and the oscilloscope to insure proper

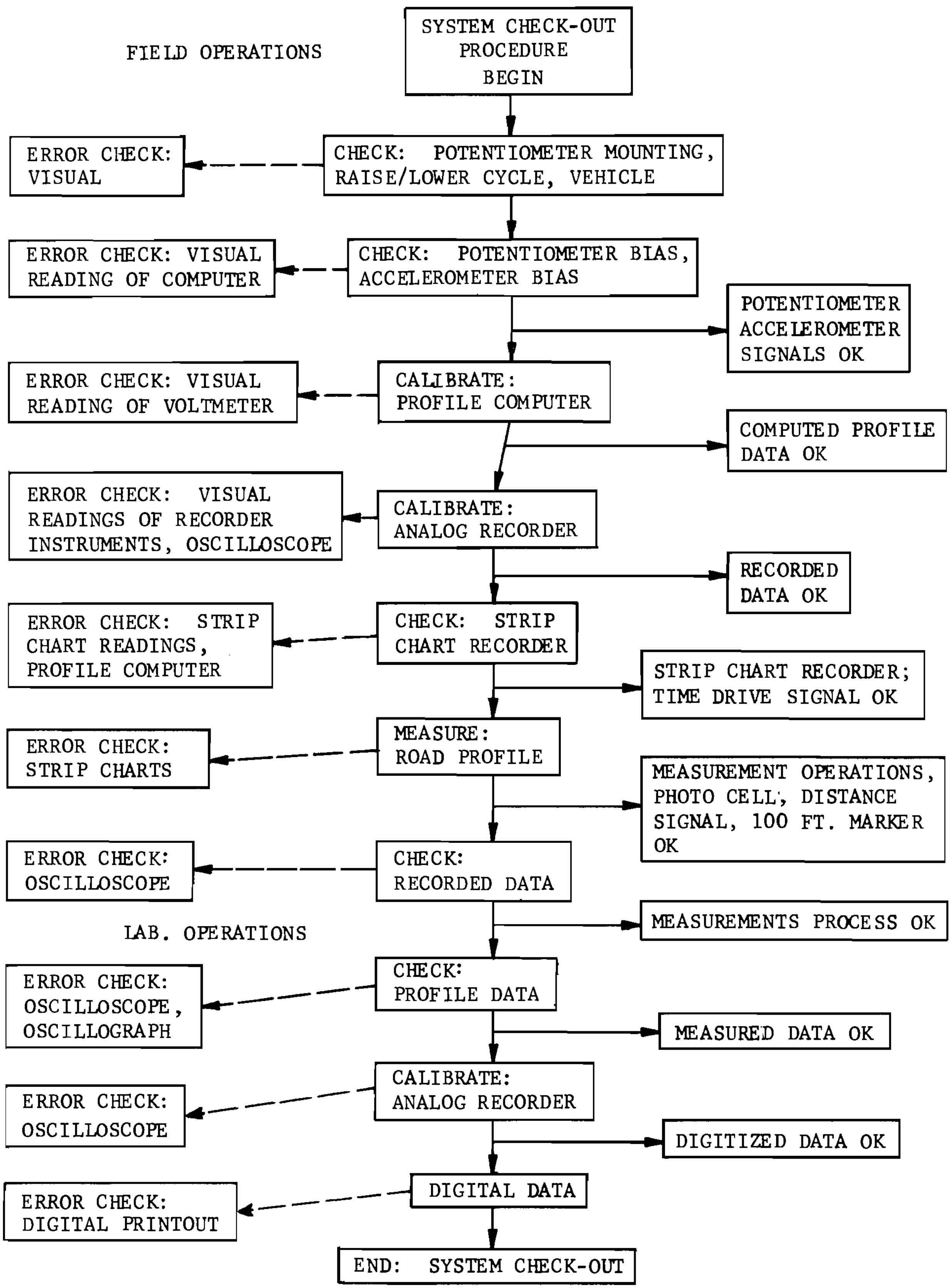

Fig 4.1. Schematic of system analysis procedure.

recording. The oscilloscope check insures that noise was not introduced into the data.

(8) The recorded data which include the profile data, photocell signal, and timing or sampling signal are brought back to the laboratory for A-D processing. Both the oscilloscope and the light beam oscillograph are then available for checking these signals for noise or other recording failures. The light beam oscillograph (wide band response) provides a high frequency hard copy output for comparison with the strip chart (limited band width) records.

(9) The Honeywell 8100 analog tape recorder should be calibrated properly to insure the playback operation for the A-D process. An inoperative recorder can result in the playback of data with considerable noise or no signal at all.

(10) Periodic checks of the digitized data should be used to confirm the validity of the digitizing process. Malfunctions in this process can add noise, provide erroneous data, or intermittently fail to sample the data signals.

REDIGITIZATION

To insure that system accuracy (determined by the least accurate subsystem - the Honeywell 8100 tape recorder) is maintained in the digitizing process, an experiment was conducted in which a known signal was recorded and then redigitized several times. The results of this experiment indicated that the accuracy of the digitizing process was within the accuracies of the Honeywell 8100 recorder, i.e., 8 bits ± least significant bit.

To obtain these results, two channels of the Honeywell 8100 magnetic tape recorder were used to record a 1000 Hertz signal.* These signals were played back into the SDS 930 computer facility, one channel into the analog input for sampling and the other into the external interrupt input to initiate the sampling process. Figure 4.2 is a pictorial description of this configuration. As noted in Chapter 2, the computer samples the analog input channels in accordance with the sampling signal. That is, each cycle of the sampling signal is used to interrupt the computer which in turn initiates a conversion process to read and store the 12-bit digitized value. By use of the same signal for the signal to be digitized and the sampling signal, a consistent set of digitized results could be obtained. This signal was digitized five

*The 1000 Hertz frequency is considered to be the upper limit of the sampling frequencies for typical data runs. The upper limit was selected because of the nature of the digitizing technique, i.e., the greater the sampling frequency the less the expected system resolution capability.

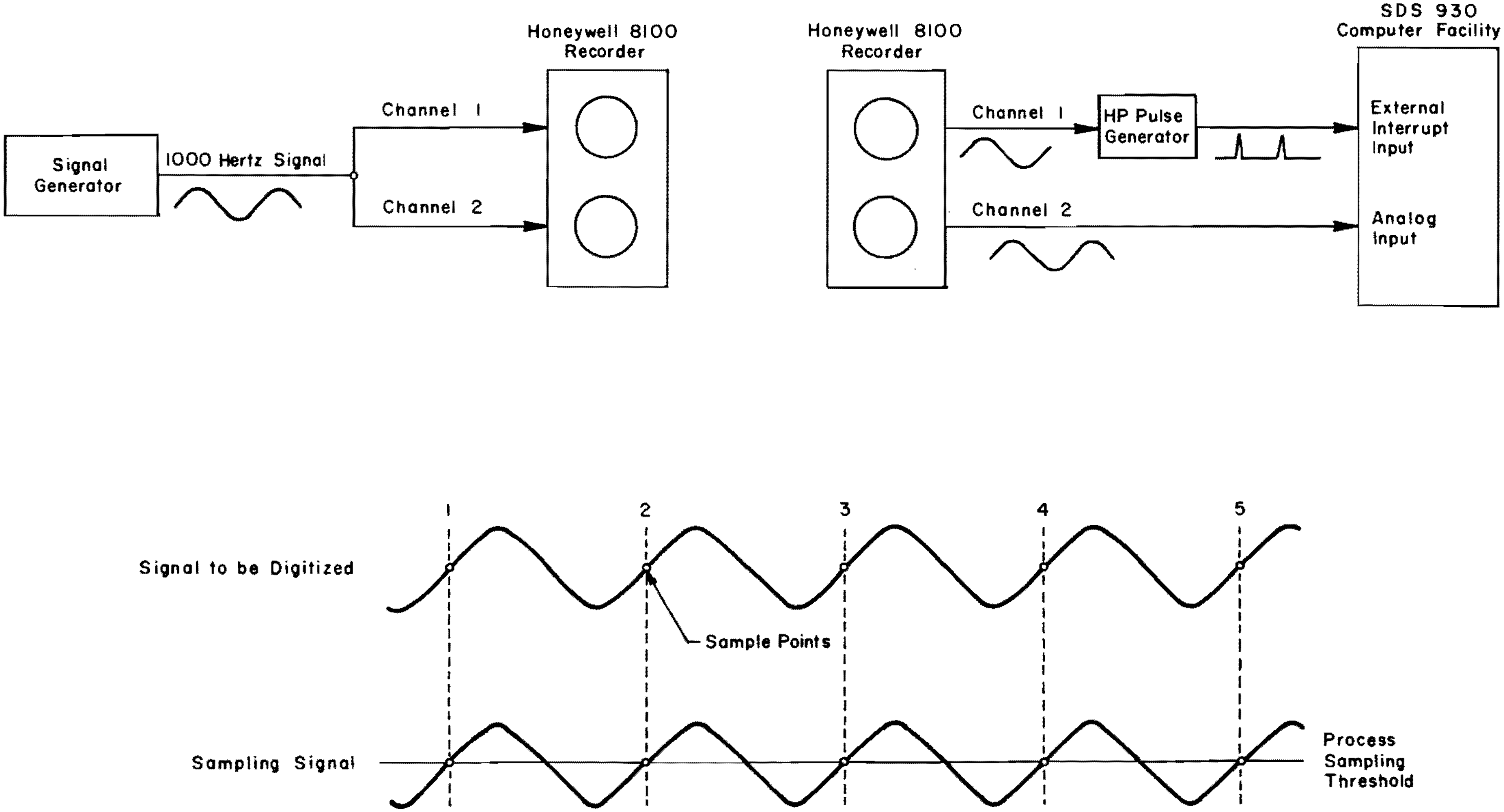

Fig 4.2. Sampling configuration.

times beginning at the same point each time, thus checking the repeatibility of the digitizing process. Table 4.1 provides the digitized results of this experiment.

As noted in Table 4.1, both 12-bit and 8-bit resolutions are indicated. This is because the A-D computer provides a 12-bit digitized value but the recording unit is only accurate to 8 bits of resolution. The 8-bit results were converted from the 12-bit values by adding 8 to each 12-bit word and then dividing by 16. As noted from Table 4.1, the largest variation between successive redigitizing is of magnitude one which is the best accuracy that can be expected from the recording device, i.e., 8 bits ± least significant bit. Thus, it is assumed that the digitizing process is within the system accuracies as established by the Honeywell 8100 recorder.*

It should be noted that redigitization of subsequent data runs confirmed these same results.

SCALE FACTOR SENSITIVITY

To scale the profile data from volts to inches, the profile computer includes the facility for providing a calibration voltage proportional to a 1-inch change in road profile. This 1-inch voltage signal, recorded prior to each profile measurement run, is digitized along with the respective profile data for a particular section. The magnitude of the digitized 1-inch step is determined by taking the difference between the average of the points before the voltage step and the average of the points after the voltage step, as shown in Fig 4.3. Once this magnitude has been determined, the digitized road profile points are divided by this scale factor value to obtain a set of scaled road profile deflections in inches. It was noted, however, that, when recording the 1-inch steps, variations existed in the magnitudes of these steps between right and left profiles for different filter-gain combinations as well as between the same channels with the same combinations for subsequent readings. The concern of such variations is easily realized if it is noted that (1) these same variations could probably be expected in the profile

*It should be emphasized that the accuracy of interest is in the entire digitizing process (i.e., using a recorded sampling signal to signal the computer to initiate the conversion process) and not in a single digitization as the SDS converted is accurate to within 12 bits ± the least significant bit. The A-D converter is checked periodically by standard SDS diagnostic programs.

TABLE 4.1. REDIGITIZATION EXPERIMENT

Sample Number	12-Bit Sample Value Repetition					8-Bit Sample Value Repetition				
	1	2	3	4	5	1	2	3	4	5
1	130	124	131	123	134	8	8	8	8	8
2	117	116	122	116	124	7	7	8	7	8
3	118	117	125	113	126	7	7	8	7	8
4	115	116	124	112	119	7	7	8	7	7
5	106	110	121	110	117	7	7	8	7	7
6	103	102	114	106	107	6	6	7	7	7
7	101	93	110	104	100	6	6	7	7	6
8	115	106	125	117	109	7	7	8	7	7
9	103	102	122	114	102	6	6	8	7	6
10	94	96	108	109	96	6	6	7	7	6
11	98	98	114	113	101	6	6	7	7	6
12	91	95	114	104	95	6	6	7	7	6
13	96	97	116	109	94	6	6	7	7	6
14	97	98	118	110	94	6	6	7	7	6
15	96	94	114	114	96	6	6	7	7	6
16	106	99	119	117	102	7	6	7	7	6
17	104	100	119	118	103	7	6	7	7	6
18	93	84	105	103	86	6	5	7	6	5
19	104	99	121	115	102	7	6	8	7	6
20	96	90	111	107	96	6	6	7	7	6
21	91	85	106	97	87	6	5	7	6	5
22	108	102	120	114	104	7	6	8	7	7
23	103	100	117	112	103	6	6	7	7	6
24	110	100	116	110	108	7	6	7	7	7
25	111	104	118	111	114	7	7	7	7	7
26	102	101	110	103	108	6	6	7	6	7
27	104	107	113	103	112	7	7	7	6	7
28	106	111	119	110	122	7	7	7	7	8
29	104	105	114	101	109	7	7	7	6	7
30	107	104	113	106	110	7	7	7	7	7
31	110	104	119	109	117	7	7	7	7	7
32	109	108	115	109	115	7	7	7	7	7
33	102	107	113	106	111	6	7	7	7	7
34	101	106	114	99	110	6	7	7	6	7
35	101	106	116	96	107	6	7	7	6	7
36	94	101	114	94	108	6	6	7	6	7
37	96	96	112	96	99	6	6	7	6	6
38	98	100	120	105	100	6	6	8	7	6
39	105	98	117	103	104	7	6	7	6	7

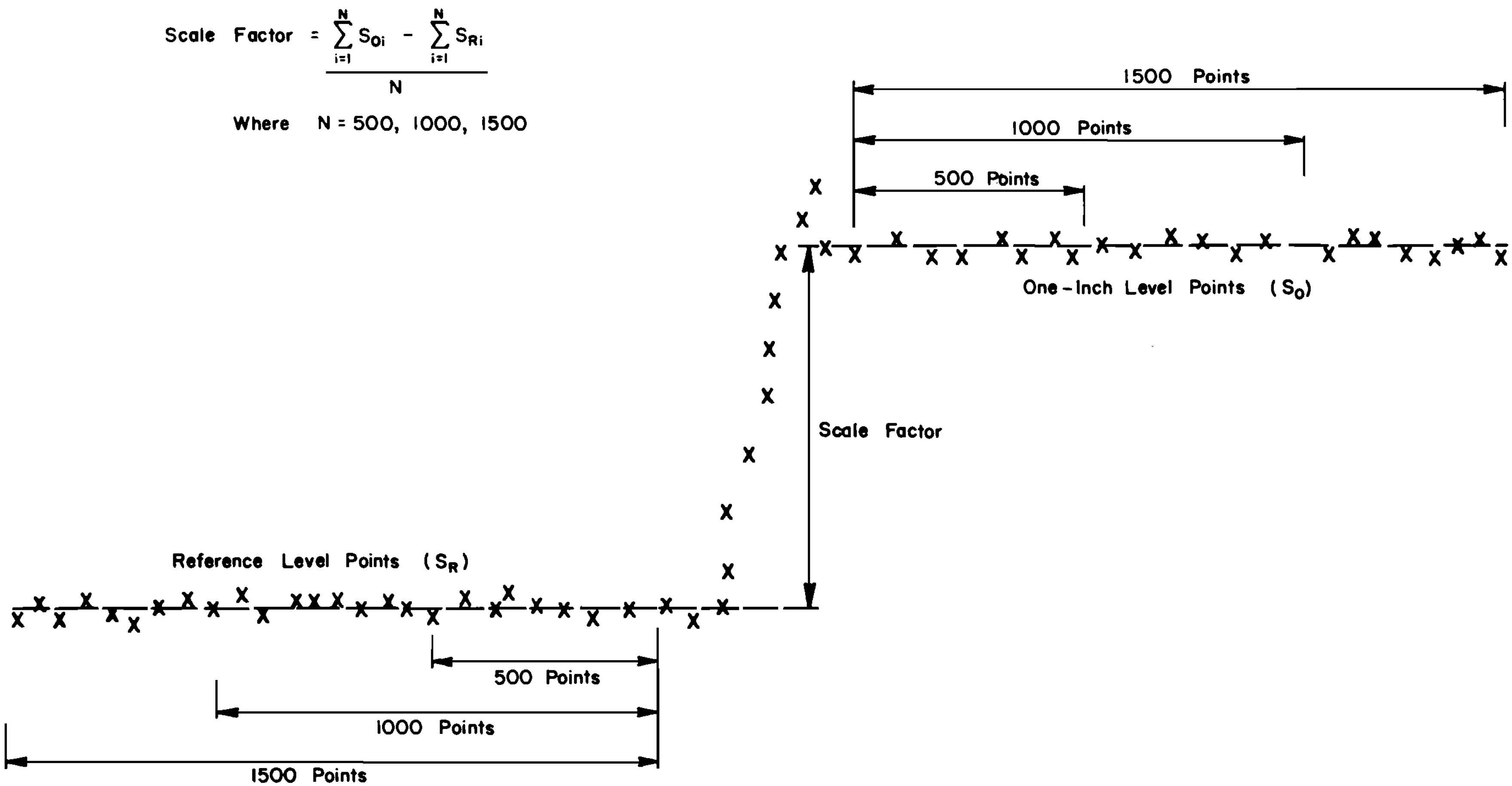

Fig 4.3. Schematic of scale factor computation.

signal itself since many of the electronic components are shared by the calibration circuitry and the profile measuring circuitry and (2) all the profile measurements are scaled by these 1-inch calibration steps.

To determine the significance of these variations on the measuring system, an experiment was conducted in which several 1-inch steps for the various filter-gain combinations were randomly obtained (See Fig 4.4 for experiment design). Since electronic components are typically heat sensitive, the experiment was conducted during the middle of an unusually warm day to observe the variations when they should be at a maximum. The 1-inch calibrations were obtained and recorded in a fashion similar to that used during a typical profile measuring operation. Recorded along with these calibration signals was an accurate 1-volt signal obtained from a DC power supply as a base for computing the differences in gain selections. The 1-inch steps were digitized and their respective scale factors determined. As noted in Fig 4.3, three averaging techniques were used (500, 1000, and 1500 point averaging) to determine if the number of points used had any effect in the scale factor computing technique.

Table 4.2 lists the computed scale factors for the various filter-gain selections. Table 4.3 shows the analysis of variance used for obtaining the above mentioned results. The analysis of variance was run on the difference between what the scale factor should have been (as obtained from the digitized measured calibration voltage) and its actual value.

From the results of this experiment, it was concluded that (1) this variation was well within the measuring accuracy of the system, and it made no difference for a particular run which filter-gain combination was used for the scale factor;* and (2) no difference existed in the averaging technique used for computing the scale factor. Subsequent experiments revealed that 100-point averaging provided adequate scale factor results and consequently it is currently used in determining scale factors.

---

*Obviously, the gain selection should be made in accordance with the gain used when measuring the road profile; however, the filter selection need not be the same. In fact, it was found that a better calibration reading is usually obtained with the Filter 4 selection. This should be expected, in view of the higher cutoff frequency of Filter 4 resulting in a more rapid attentuation of the system to the zero equilibrium point which is used in the scale factor computing technique as the base or reference value.

				Profile Signal							
				Right Profile				Left Profile			
				Filter				Filter			
				1	2	3	4	1	2	3	4
Gain	1	Technique	3								
			2								
			1								
	2	Technique	3								
			2								
			1								

(4 Observations per cell)

Fig 4.4. Scale factor experiment design.

TABLE 4.2. SCALE FACTOR EXPERIMENT DATA

Test (Filter-Gain)	Truck Reading Actual Value Right	Left	Computer Reading 500 Right	Left	1000 Right	Left	1500 Right	Left	File No.
1 - 1	306.1	302.8	292.7	292.0	292.8	292.0	293.1	292.4	9
1 - 1			315.8	300.7	319.1	296.2	320.3	294.9	10
1 - 1			302.9	295.8	304.5	294.4	303.9	294.3	12
1 - 1			300.4	294.8	301.5	295.0	298.4	295.6	22
2 - 1	301.1	305.9	293.5	293.4	290.2	293.0	290.4	293.1	3
2 - 1			293.4	293.2	287.2	292.2	288.3	292.7	8
2 - 1			293.6	293.6	293.2	293.7	292.4	293.5	18
2 - 1			293.5	293.4	290.2	293.0	290.4	293.1	23
3 - 1	300.9	305.9	291.2	292.6	291.3	292.4	292.2	292.6	7
3 - 1			292.2	294.3	292.2	293.8	292.1	293.7	11
3 - 1			291.1	292.4	291.3	294.3	291.4	293.9	17
3 - 1			286.7	296.7	288.6	297.0	290.3	296.8	30
4 - 1	300.0	306.2	293.3	289.9	291.8	290.5	291.1	290.6	2
4 - 1			288.5	289.6	288.7	289.3	288.7	289.1	5
4 - 1			291.5	294.3	291.6	294.5	291.7	295.5	25
4 - 1			291.0	295.1	292.6	294.7	292.4	294.6	27
1 - 2	607.2	608.5	580.2	589.3	578.0	590.4	576.7	590.5	4
1 - 2			583.8	592.5	583.0	592.6	583.2	593.2	15
1 - 2			590.4	593.1	590.7	592.4	590.9	591.9	20
1 - 2			589.7	596.7	588.4	602.3	588.3	600.6	26
2 - 2	601.7	609.6	602.4	600.9	604.8	600.7	605.8	600.4	13
2 - 2			595.2	599.2	595.5	599.1	596.0	599.2	19
2 - 2			567.6	604.9	583.7	605.0	588.6	604.9	32
2 - 2			593.7	602.8	593.0	602.7	592.3	602.6	29

(continued)

TABLE 4.2. (continued)

Test (Filter-Gain)	Truck Reading Actual Value		Computer Reading 500		1000		1500		File No.
	Right	Left	Right	Left	Right	Left	Right	Left	
3 - 2	602.3	613.6	593.9	594.5	592.2	594.6	591.4	594.0	1
3 - 2			590.1	594.9	590.2	594.8	590.5	595.0	6
3 - 2			592.8	595.6	593.2	596.8	593.1	597.5	16
3 - 2			586.3	600.5	589.0	599.7	591.0	600.5	21
4 - 2	600.5	611.9	590.3	594.5	590.6	595.6	590.5	595.7	14
4 - 2			591.9	597.8	592.0	599.4	591.8	599.6	24
4 - 2			591.6	600.0	591.9	600.2	591.6	600.4	28
4 - 2			593.0	601.4	592.8	601.1	589.7	595.3	31

TABLE 4.3. ANALYSIS OF VARIANCE SCALE FACTOR EXPERIMENT OF TABLE 4.2

Source	dF	SS	MS
Filter (F)	3	195.97	65.32
Gain (G)*	1	487.05	487.05
F × G*	3	1,715.58	571.86
Side (S)	1	213.36	213.36
S × F	3	258.00	86.00
S × G	1	140.77	140.77
S × F × G	3	516.98	172.32
Error (a)	45	2,723.69	60.70
(Replication (R), R × F, R × G, R × F × G, R × S, R × S × F, R × S × G, R × S × F × G)			
Technique (T)	2	0.71	0.36
T × F	6	9.26	1.54
T × G	2	8.29	4.14
T × F × G	6	45.93	7.65
T × S	2	3.54	1.77
T × S × F	6	4.78	0.80
T × S × G	2	2.70	1.35
T × S × F × G	6	54.52	9.09
Error (b)	96	268.70	2.80
(T × R, T × R × F, T × R × G, T × R × F × G, T × R × S, T × R × S × F, T × R × S × G, T × R × S × F × G)			
Total	191		

*Significance is expected since the gain is a multiplication factor.

SYSTEM FREQUENCY RESPONSE

The frequency response of the high-speed road profile measuring system to various road profile wavelengths is extremely important in highway profile analysis. For example, the gain attentuation and phase shift of the measuring system must be accounted for when determining the various frequencies that constitute a particular road profile. Figure 4.5 illustrates the major subsystem responses which contribute to this overall response. As noted in the figure the total system response consists of the individual responses of the vehicle suspension system, the accelerometer, the potentiometer, and the profile computer. Assuming the vehicle suspension system has the form shown (in particular a critical frequency ω of 6 radians per second) the overall system response curves for each filter can be derived in a similar manner, as shown in Fig 4.6 for Filter 4. Both ideal and actual filter and integrator action are shown in Fig 4.6 and as may be noted the actual frequency response of the profile computer follows quite closely the ideal curves. Measurements of the other filters revealed similar proximity between ideal and actual values and thus, for all practical purposes, the ideal curves may be used for determining the frequency response of the overall measuring system. Figures 4.7(a) and 4.7(b) depict the response curves and the associated phase shift for all four filters. The upper cutoff frequency shown in Fig 4.7(b), of 1000 radians per second, holds for all curves as it is a function of the potentiometer isolation amplifier.

SENSOR WHEEL ANALYSIS

As noted in Chapter 2, the life of the sensor wheel has been found to be much shorter than expected. In fact, it has been found necessary to replace this wheel about every 400 to 500 miles of road use. Since the cost of the wheel is about \$500, this wear is considered excessive. Consequently, investigations are currently in progress to find a less expensive, but usable, wheel. These investigations hopefully will also provide some measure of the amount of wear a wheel can be subjected to and still provide meaningful results.

Investigations are also in progress to identify the influence of wheel characteristics, such as wheel bounce, on the measured data. Use of the profilometer to date has indicated the existence of a periodic wave form of about 55 Hertz in all data. This wave is generally more prevalent in roads

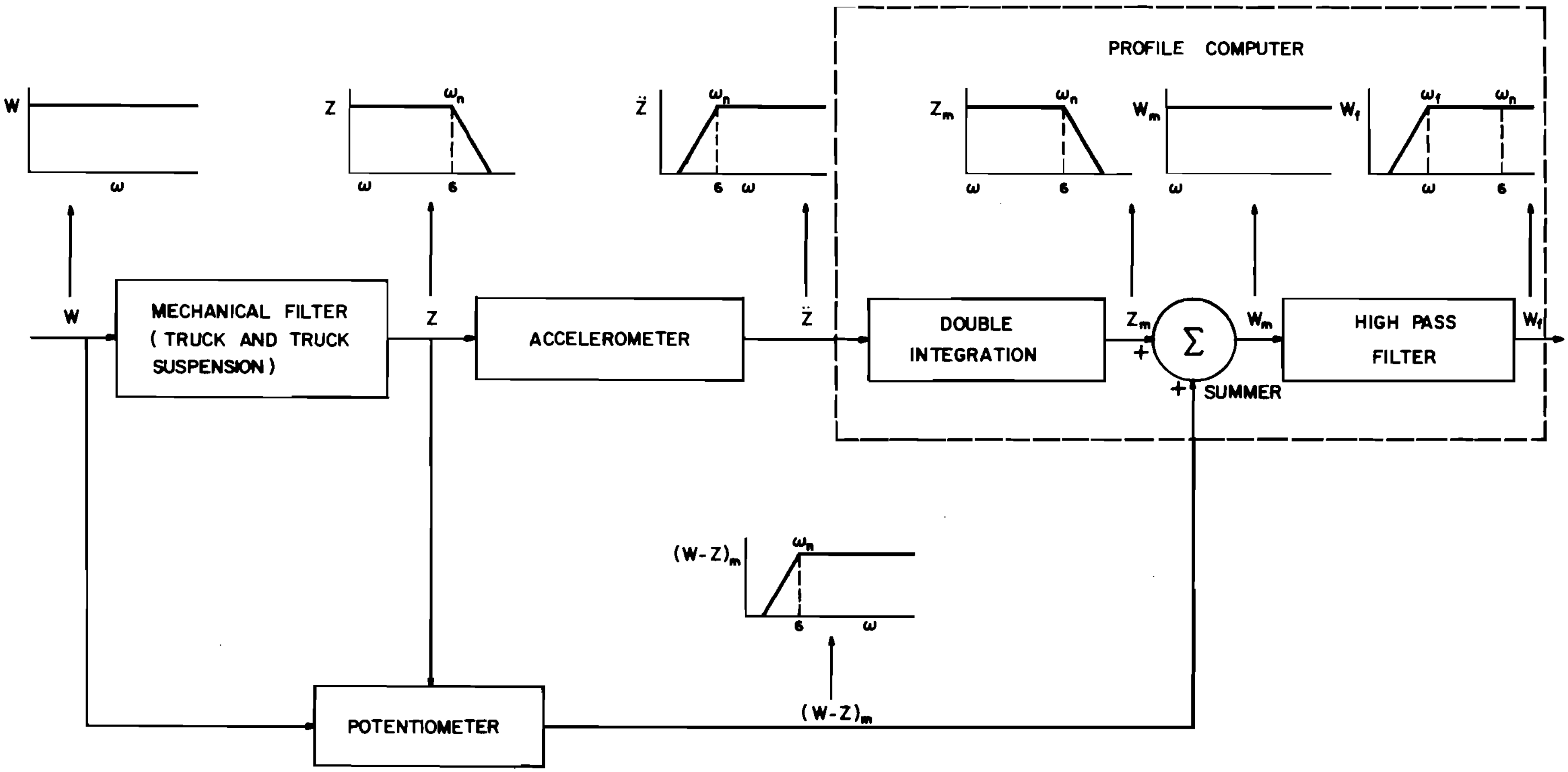

Fig 4.5. Subsystem frequency responses.

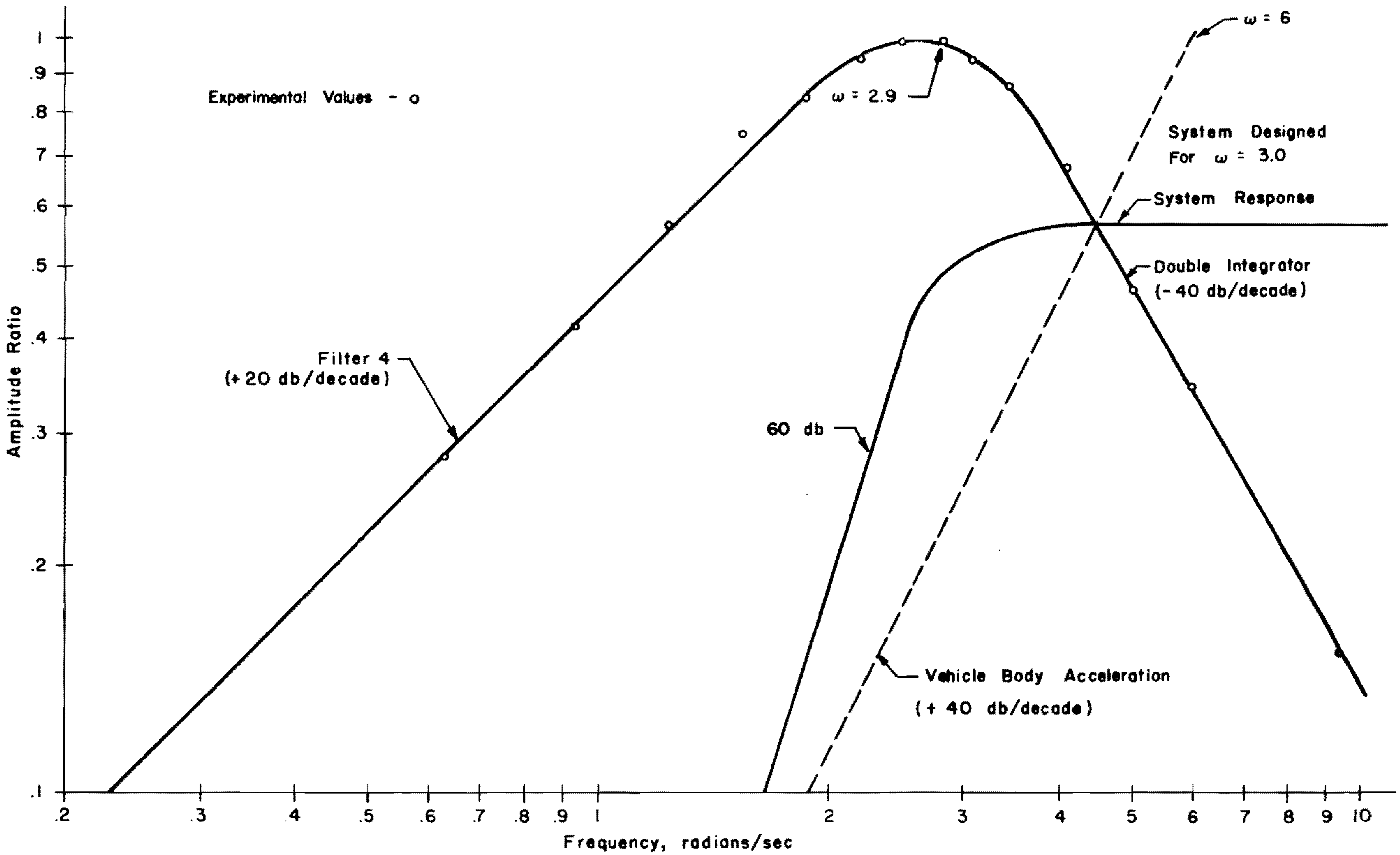

Fig 4.6. Bode plot of system response

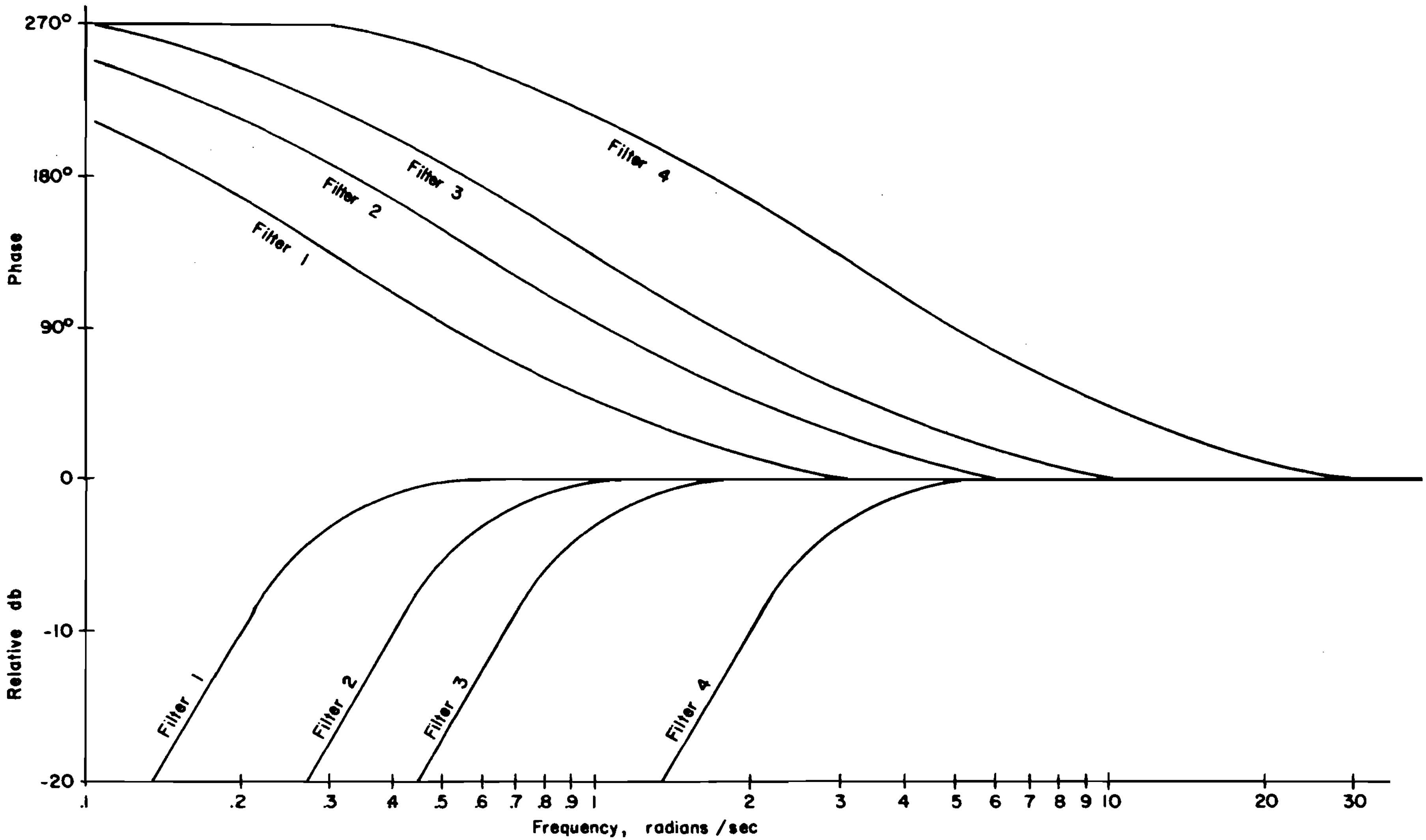

Fig 4.7a. Low frequency system response.

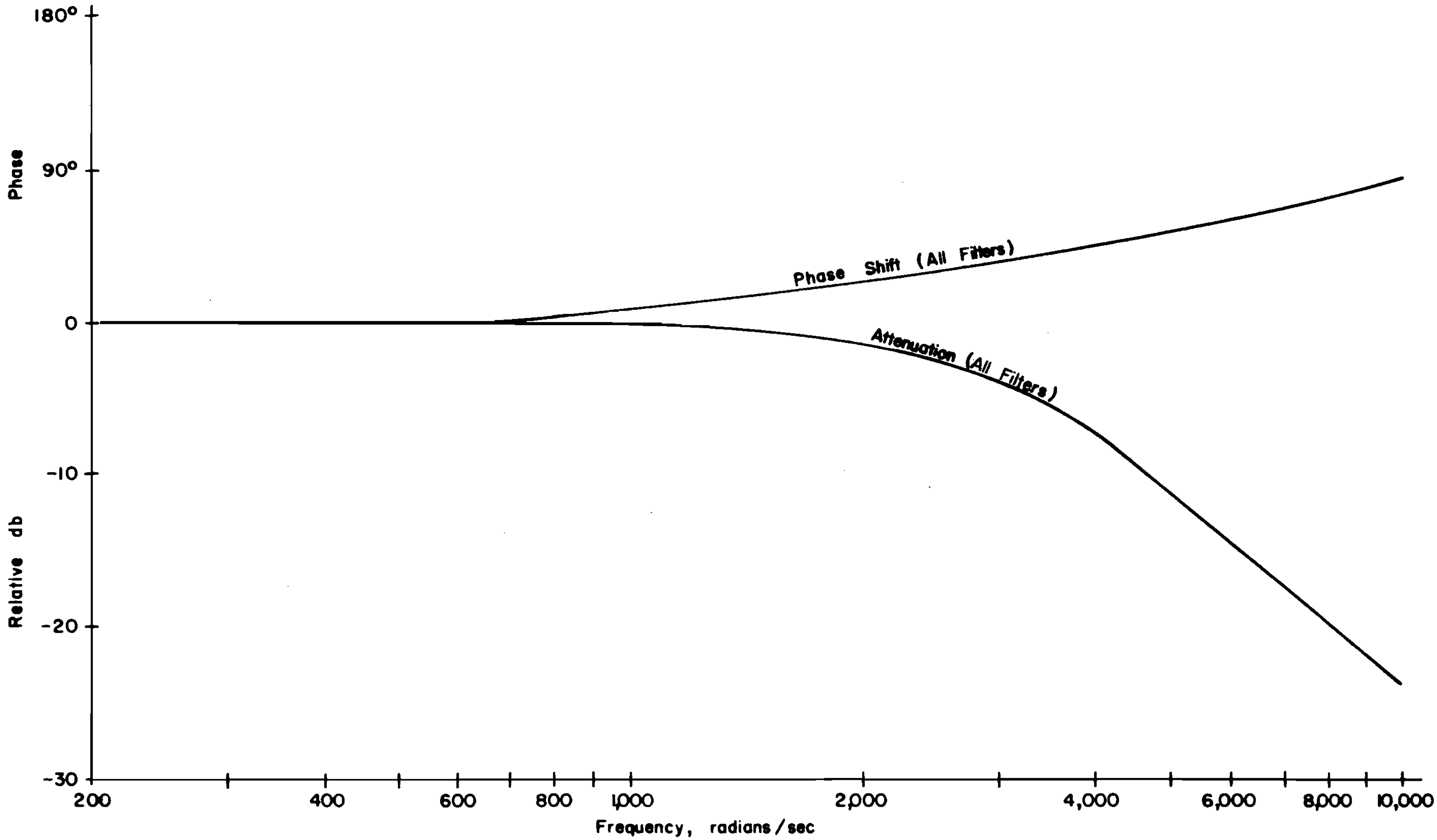

Fig 4.7b. High frequency system response.

with rough textures such as those with surface treatments. Power spectral analysis and coherence on selected combinations of various surface treatments and road types and the analysis of variance are some of several analysis techniques being employed to identify and determine the significance of these wheel characteristics.

CHAPTER 5. SUMMARY AND CONCLUSIONS

This report gives a detailed description of a high-speed road profile measuring system, including profilometer calibration procedures, filter-speed selection and other general operating criteria, analog-to-digital operations, and system checkout and data validation techniques.

The profilometer provides an accurate account of low frequency components in the road profile. The higher frequency data have been found to be somewhat distorted due to wheel bounce at operating speeds above 34 mph. The amount of distortion is a function of vehicle speed and profile roughness. Studies are continuing in order to determine the amount and significance of these distortions.

In general the amount of time required for processing profile data with the A-D facility and profile summary routines is often lengthy, especially when immediate results are desired. Thus there appears to be some advantage in providing a profile summary device in conjunction with the profile computer which would provide immediate estimates of road roughness or other such characteristics while making a profile run. If such a system is desirable to the sponsors, however, an evaluation of the accuracies of such devices must be carefully determined.

The weakest link in the measuring system appears to be the sensor or road-following wheel. Considering the high cost of these wheels, the usable life, ranging from 100 to 500 miles, is too short. The wheels have been found very susceptible to cutting and the frames are often damaged when measurements are made on rough portland cement concrete pavements. To remedy this problem, two substitute wheels are currently being evaluated. The cost of these wheels is less than $50. From comparisons of initial test runs, there appear to be some differences in the upper frequencies of the profile made with one of the replacement wheels when compared with the original equipment wheel. Further analysis will indicate if these differences are within acceptable error limits of the overall system.

Extreme care is required in general operation of this equipment because of the many possible sources for introducing erroneous mechanical and electrical noise into the profile. Because of this problem, we have found it necessary to monitor the data with an oscilloscope after data runs. (The oscilloscope is necessary because of the inability of the Brush recorder to respond to most high frequency noise.)

CHAPTER 6. APPLICATION OF RESEARCH RESULTS

Since an adequate operating manual was not provided by Law Engineers, this report provides a detailed calibrating and operating manual for future use by the Texas Highway Department personnel. This device will continue to be used to evaluate PSI in this research project, to evaluate roughness and the road profile for Project 118, to evaluate profiles in conjunction with Project 123, and for special runs for the Texas Highway Department.

In the future this equipment has specific uses in the following areas:

(1) To aid in the establishment of priority for major maintenance, reconstruction and relocation. The roughness values available with this equipment along with information from traffic studies could be used to make objective rankings for various pavement sections.

(2) To aid the design engineer in the determination of the degree of success with which his design has met the design criteria and to help him learn the causes for failure. To successfully evaluate a design system, accurate measurements of the system output function must be made during the entire design life of the pavement. Such measurements will provide an objective indication of the performance and the success of the particular design.

(3) To aid in the establishment of the levels of roughness which are acceptable for new construction.

In order to make the profilometer a more useful tool it is recommended that further studies be conducted to differentiate between profile data and erroneous data introduced from wheel bounce and noise. This is being accomplished using analysis techniques recently developed at the Center for Highway Research. These techniques will help in establishing the undesirable frequency ranges.

Briefly, the procedures used in such analysis would involve using digital filtering techniques to remove various frequency ranges and noting the effects on the resulting profile data and summary statistics. Power and cross-power spectrum analysis, regression analysis, and analysis of variance are useful tools in denoting the significance of these effects.

It is also recommended that studies be continued to develop better techniques for data validation during the measuring process for early detection of noise or equipment malfunctions.

In conjunction with pursuing the data validation problem a suitable in-vehicle summary device could be used as an indicator of erroneous profile data. Such a device would also be of great value in providing rapid road profile evaluation. The accuracy of such a device would probably not be as great as existing processing techniques but would significantly enhance the use of the SD Profilometer in the field.

REFERENCES

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2. "The Surface Dynamics Profilometer," K. J. Law Engineers, Inc., Detroit, Michigan.

3. Hudson, W. Ronald, "High-Speed Road Profile Equipment Evaluation," Research Report No. 73-1, Center for Highway Research, The University of Texas, Austin, January 1966.

APPENDIX 1

SYSTEM PROBLEMS

APPENDIX 1. SYSTEM PROBLEMS

As in all newly developed systems, a number of problems had to be solved before a workable measuring system could be developed. The majority of these problems occurred in the profilometer. As noted, however, the profilometer used in this system was the first such device manufactured and hence most of these problems were not unreasonable, although there did appear to be an unusually large number of problems associated with the vehicle engine. The problems often resulted in considerable frustration and delays.

The following is a list of some of the more serious problems encountered and the steps taken to alleviate them.

1. Potentiometer

   a. Failure of potentiometer wiper shaft to wheel assembly connection: the wiper shaft connection was redesigned for a male type connector.

   b. Sleeves on the wiper arm would not maintain their structural integrity: these sleeves were originally sweated on; they are now welded on.

   c. The bearings for the wiper shaft were damaged several times when the wheel assembly was raised because of excessive travel in the hydraulic actuator: limit switches were replaced to provide positive limit adjustments.

2. Distance Pulse Generator

   a. Poor connection of some of the leads in the pulse generator resulted in the intermittant loss of the distance pulse: the leads were resoldered.

   b. The temperature environment of the Veeder-Root generator exceeded the design requirements, resulting in the loss of the distance pulse signal: the Schmitt trigger circuit, which was breaking down, was bypassed.

3. Photocell

   a. The power leads to the photocell lamp were severed: the leads were replaced.

   b. Continual breakage of the photocell lamp was noted: a better mounting technique was developed.

4. Automatic Speed Control - the speed control unit would not operate properly: the motor and drive gear in the speed control unit were replaced.

5. Power Supply - the Brush equipment would not operate on the square wave 500 va inverter: a "Power Com" sine wave inverter for the Brush equipment was installed and the Brush pulse generator was repaired.

6. Trailing Arm - Hydraulic Life

   a. The trailing arms would not catch properly in some situations: limit switches, the hydraulic actuator, and the timing control switch were adjusted.

   b. Trailing arm stabilizer spring failures: an inexpensive spring was found and large quantities were purchased for replacement.

   c. Potentiometer shaft mount yokes on the trailing arms frequently failed: the support brackets were welded to yokes.

7. Tape Recorder

   a. Recorder delivered inoperative from Law Engineering: the recorder was sent to Honeywell for repair.

   b. Discriminator and record zero adjustment trim-pot failure: Honeywell replaced all trim-pots.

8. Profile Computer

   a. Capacitor mounts failed due to vibrations: mounting brackets were redesigned to withstand vibration.

   b. Integrated circuit failure, J-K flip-flop in counter circuit: the circuit was replaced.

9. Truck Engine

   a. Vehicle delivered with burned out valves and rod bearings: the engine was rebuilt.

   b. Problem with frequent overheating of engine: the fan was changed and a shroud was installed over the fan.

   c. Engine timing problem: the timing gear was replaced.

APPENDIX 2

A-D PROGRAM SOURCE LISTING

```
*  A TO D PROGRAM, CENTER FOR HIGHWAY RESEARCH
      DIMENSION NDATA[3000], IDENT[5]
    2 FORMAT[10I8]
    3 FORMAT[/,$FN=$,I5,$, NR=$,I5,$, NCLR=$,I5,$, NC=$,I8,
     1       $, SR=$, I5]
  110 FORMAT[$TYPE FILE NO., SAMP. IDENT, O,$]
   33 FORMAT[$DATA CLOBBERED--REDUCE SAMPLING RATE$]
    1 FORMAT[$FILE NUMBER,O$]
   60 FORMAT[$F=$,I3,$ NC=$,I8]
      REWIND 1
      LOC = 0
 26   FORMAT ($ENTER 0 TO DEACTIVATE SKS LINE 1 $)
      TYPE 26
 40   IERR = 0
      ACCEPT 2,NKSG,IERR
      IF (IERR)40,41,40
 41   CONTINUE
      TYPE 20
20    FORMAT[$ENTER NUMBER OF CONVERSION CHANNELS$]
80    IERR = 0
      ACCEPT 2,NCH,IERR
      IF [IERR]80,81,80
81    TYPE 21
21    FORMAT ($ENTER INTERRUPT CYCLE COUNT$)
83    IERR =0
      ACCEPT 2,ICY,IERR
      IF (IERR)83,84,83
 84   CALL CCSET (NCH,ICY,NKSG)
   66 IF[SENSE SWITCH 2] 152, 6
  152 NFILT = -1
      GO TO 11
    6 TYPE 1
   10 IERR=0
      ACCEPT 2,NFILT,IERR
      IF[IERR] 10, 11, 10
   11 CALL FILOC[IDENT,NFILT,LOC]
      CALL CHRDY
      IF (SENSE SWITCH 1)50,88
88    CONTINUE
      IF (SENSE SWITCH 2)93,92
93    IF (SENSE SWITCH 3)91,94
94    IF (SENSE SWITCH 4)95,92
91    PRINT 60,IDENT(1),IDENT(4)
      GO TO 95
92    CONTINUE
      TYPE 60, IDENT[1], IDENT[4]
95    CONTINUE
      IF[SENSE SWITCH 2] 8, 9
    9 TYPE 110
   12 IERR=0
      ACCEPT 2, IDENT[1], IDENT[5], IERR
      IF[IERR] 12, 13, 12
    8 IDENT[1] = IDENT[1] + 1
   13 CALL ADCON[NDATA,NGO,IDENT]
      GO TO [51, 52], NGO
   52 CALL NTPRDY
   54 CALL BCKONE
      IF [IFILMK[NDUM]] 53, 54, 54
   53 CALL NTPRDY
```

```
   51 CALL FILMRK
      CALL FILMRK
      CALL NTPRDY
      CALL BCKØNE
      LØC = -1
      CALL CHRDY
      CALL INTDIS
      GØ TØ [50, 47], NGØ
   47 TYPE 33
50    IF(SENSE SWITCH 2)76,75
76    IF(SENSE SWITCH 3)77,78
77    PRINT 3,(IDENT(I),I=1,5)
      GØ TØ 66
78    IF (SENSE SWITCH 4)66,75
75    TYPE 3,(IDENT(I),I=1,5)
      GØ TØ 66
      END
      SUBRØUTINE FILØC[IDENT,NFILE,LØC]
      DIMENSIØN IDENT[5]
      CALL CHRDY
      CALL NTPRDY
      IF[LØC] 40, 42, 31
   40 CALL BCKØNE
      LØC = 1
      GØ TØ 31
   42 IF[NFILE] 41, 31, 41
   41 CALL FWDØNE
      LØC = 1
   31 IF[NFILE] 4, 2, 3
   11 FØRMAT [$END ØF DATA$]
    2 REWIND 1
      CALL FILMRK
      LØC=1
      GØ TØ 23
    3 CALL NTPRDY
   15 CALL FWDØNE
      IF[IFILMK[J]] 16, 15, 15
   16 CALL NTPRDY
      CALL BCKØNE
      CALL BCKØNE
      CALL NTPRDY
      CALL TAPIN[IDENT, 1, 5, 4, 1, ITPFLG]
      CALL NTPRDY
      IF[NFILE - IDENT[1]] 17, 18, 19
   17 NDØ = IDENT[2] + 2
      DØ 20 I= 1, NDØ
      CALL BCKØNE
   20 CØNTINUE
      GØ TØ 3
   18 NDØ = IDENT[2] + 1
      DØ 21 I= 1, NDØ
      CALL BCKØNE
   21 CØNTINUE
      GØ TØ 23
   19 CALL FWDØNE
      CALL FWDØNE
      IF[IFILMK[J]] 22, 15, 15
    4 CALL NTPRDY
   24 CALL FWDØNE
      IF[IFILMK[J]] 25, 24, 24
```

```
25 CALL FWDONE
   IF(IFILMK(J)) 26, 24, 24
26 CALL NTPRDY
   CALL BCKONE
   CALL BCKONE
   CALL BCKONE
   CALL NTPRDY
   CALL TAPIN(IDENT, 1, 5, 4, 1, ITPFLG)
   CALL FWDONE
43 LOC = -1
23 CALL NTPRDY
   RETURN
22 TYPE 11
   CALL NTPRDY
   CALL BCKONE
   GO TO 43
   END
   SUBROUTINE TAPIN(NDATA, NST, NREAD, NCHAR, NUNIT, ITPFLG)
   CALL NTPRDY
 3 CALL RTINIT(NDATA, NST, NREAD, NCHAR, NUNIT, ITPFLG)
   CALL RNUCNT
 7 CALL TPRD
 8 IF(ITPFLG) 8, 10, 11
11 CALL RTPEND
10 RETURN
   END
```

```
$FILMRK PZE
       SKS 010411 TRT 0,1
       BRU $+2
       BRU $-2
       SKS 014000 CATO
       BRU $-1
       EOM *03671
       POT =834*/14
       SKS 010411 TRT 0,1
       BRU $+2
       BRU $-2
       EOM 02051
       MIW *017170000
       EOM 014000
       SKS 010411
       BRU $+2
       BRU $-2
       SKS 014000 CAT 0
       BRU $-1
       BRR FILMRK
       END
$INTDIS PZE
       LDA ST200
       STA 0200
       LDA ST33
       STA 033
       LDA ST31
       STA 031
       BRR INTDIS
ST200  BRM DONOTH
ST33   BRM DO3
ST31   BRM DO1
DO1    PZE
      BRU *DO1
DO3    PZE
       BRU *DO3
DONOTH  PZE
       BRU *DONOTH
$ST200,ST33,ST31
$CHRDY  PZE
       SKS 014000
       BRU $-1
       BRR CHRDY
$NTPRDY  PZE
       TRT 0,1
       BRR NTPRDY
       BRU $-2
*FWDONE AND BACKONE HANG UP UNTIL AFTER OPERATION
*COMPLETE
$BCKONE PZE
       SRB 0,1,4
       BRM NOW
       BRR BCKONE
$FWDONE PZE
         SFB 0,1,4
         BRM NOW
         BRR FWDONE
NOW      PZE
         SKS 012611  GAP
```

```
          BRR NØW
          SKS 010411   TRT
          BRR NØW
          BRU NØW+1
$DISC     PZE
          LDA ØNE
          IET
          CNA
      STA WHTDØ
        DIR
        BRR DISC
$CØN     PZE
        SKN WHTDØ
        EIR
        BRR CØN
WHTDØ RES 1
ØNE   DATA 1
*FUNCTIØN IFILMK(NDUMMY)
*RETURNS -1 IF (EØF), +1 IF (NØ EØF)
$IFILMK PZE
        LDA =1
        SKS 013610
        CNA
        BRR IFILMK
        END
XSD       ØPD 010000000
$RTINIT PZE
          BRM 201SYS
          XSD IDATA
          XSD NST
          XSD NWRT
          XSD NCHAR
          XSD NUNIT
          XSD ITPFLG
          BRM 202SYS
          STX SAVX
          LDA *NCHAR
          SUB ØNE
          MUL CØNST
          RSH 1
          DSC 0
          CBA
          ADD *NUNIT
          ADD READ
          STA RBT
          SUB READ
          ADD SCNRV
          STA RSB
         LDA 031
          STA SAV31
          LDA 033
          STA SAV33
          LDA MØNE
          IET
          CNA
          STA SAVEN
          BRM CLRINT
          EAX ØPCØMP
          STX 033
          EAX CKWRT
```

```
         STX WHRCK
         LDX SAVX
         LDA ØNE
         STA *ITPFLG
         BRR RTINIT
$RNUCNT  PZE
         CLB
         LDA *NWRT
         LSH 016
         STA WDCNT
         BRR RNUCNT
$TPRD    PZE
         SKN *ITPFLG
         BRU $+2
         BRR TPRD
         LDA WDCNT
         MRG IDATA
         ADD *NST
         ADD MØNE
         STA WDPØT
         EXU RBT
         PØT WDPØT
         LDA MØNE
         STA *ITPFLG
         BRR TPRD
CLRINT   PZE
         LDX MBØP
         EAX DØNØTH
         STX 031
         STX 033
         EIR
         BRR CLRINT
DØNØTH   PZE
         BRU *DØNØTH
ØPCØMP   PZE
         BRU *WHRCK
CKWRT    CET 0
         BRU $+8
         STA SAVA
         LDA THREE
         STA CNT
CKEND    LDA ØNE
         STA *ITPFLG
         LDA SAVA
         BRU *ØPCØMP
         TRT 0,1
         BRU $+2
         BRU $-2
READCK   SKR CNT
         BRU $+12
         STA SAVA
         CLA
         STA *ITPFLG
         LDA THREE
         STA CNT
         LDA SAVA
         STX SAVX
         EAX CKWRT
         STX WHRCK
         LDX SAVX
```

```
          BRU *ØPCØMP
          EXU RSB
          PØT WDPØT
          STX SAVX
          EAX RERD
          STX WHRCK
          LDX SAVX
          BRU *ØPCØMP
RERD      EXU RBT
          PØT WDPØT
          STX SAVX
          EAX CKWRT
          STX WHRCK
          LDX SAVX
          BRU *ØPCØMP
$RTPEND   PZE
          SKN SAVEN
          DIR
          LDA SAV31
          STA 031
          LDA SAV33
          STA 033
          BRR RTPEND
RBT       RES 1
RSB       RES 1
IDATA     RES 2
NST       RES 2
NWRT      RES 2
NCHAR     RES 2
NUNIT     RES 2
ITPFLG    RES 2
SAVX      RES 1
SAV31     RES 1
SAV33     RES 1
SAVEN     RES 1
SAVA      RES 1
WHRCK     RES 1
WDPØT     RES 1
WDCNT     RES 1
CNT       RES 1
CØNST     DATA 128
THREE     DATA 3
ØNE       DATA 1
MØNE      DATA -1
MBØP      DATA 04300000
READ      DATA 0243010
SCNRV     DATA 0247030
          END
*A/D CØNVERSIØN PRØGRAM
XSD       ØPD 010000000
$ADCØN    PZE
        BRM 201SYS
        XSD NDATA
        XSD NGØ
        XSD IDENT
        BRM 202SYS
        STX SAVX
        BRM CHRDY
        BRM INTDIS
        CLR
```

```
      LDX =-3
      EIR
      LDA =$+2
      STA DUMMY
      BRX $+2
      BRU $+2
      BRU *DUMMY
      LDA =START
      STA RETRN
      LDA NDATA1
      ADD =1500
      STA ARRAY
      ADD =1500
      STA ARRAY1
      LDX =040000
      EAX INTLB1
      STX INTLBC
      STB NREC
      LDA =1500
      LCY 14
      MRG NDATA
      STA WDPBT1
      ADD =1500
      STA WDPBT2
      LDX =-1500
      STX FLAG
      LDA BR33
      LDB BR200
      SKS 010411  TRT 1
      BRU $+2
      BRU $-2
      SKS 014011  FPT 1
      BRU $-1
      STA 033
      CLA
*START SKS
        SKS   034200          LINE 0
        BRU $+2
        BRU $-2
        STA   SGST
        LDA   SG
        SKE   =0
        BRU   $+2  CHECK LINE 1
        BRU   $+6
        SKS   034100   LINE 1
        BRU   $+2
        BRU   $-2
        LDA   =0
        STA   SG   CLEAR SKS 1 FLAG
        LDA   SGST
        STB 0200
        BRU START
BR33    BRM INT33
BR200   EXU PNT200
$START EQU $
*FINISH SKS
        SKS   034200          LINE 0 OFF
        BRU   $+2
      BRU FINISH
      SKG =1
```

```
      BRU START
      BRU ERRBR
FINISH LDB ST200
      STB 0200
        LDB   *KSG
        STB   SG
      LDB =$+2
      STB RETRN
      SKN FLAG
      BRU $-1
      SKG =0
      BRU $+3
      STA FLAG
      BRU *INTLBC
      LDB =IDWRIT
      STB RETRN
      STX DUMMY
      LDA =1500
      ADD DUMMY
      STA NLAST
      SKG =0
      BRU IDWRIT
      CLA
      LDB =1
      SKB NREC
        BRU   NBSKIP+2
        BRU   $+3
      BRX $+2
      BRU NBBR
      STA *ARRAY
      BRU $-3
NBSKIP BRX $+2
      BRU NBBR
      STA *ARRAY1
      BRU $-3
NBBR  ADD =1
      STA FLAG
      BRU *INTLBC
IDWRIT SKN FLAG
      BRU $-1
      LDX =1
      STX *NGB
      LDB NREC
      STB *IDENT1
      BRX $+1
      LDB NLAST
      STB *IDENT1
      BRX $+1
      LDA NREC
      SKG =0
      BRU $+5
      SUB =1
      MUL =1500
      LSH 23
      ADD NLAST
      STA *IDENT1
      STX FLAG
      LDX =-1500
      LDA =5*/14
      MRG IDENT
```

```
        STA DUMMY
        EOM *010000
        POT DUMMY
        EOM 03651
        SKN FLAG
        BRU $-1
EXIT    SKS 010411 TRT 0,1
        SKS 014000 CAT 0
        BRU $-2
        BRM INTDIS
        DIR
        LDX SAVX
        BRR ADCON
ERROR   DIR
        LDB =2
        STB *NGO
        LDB ST200
        STB 0200
        EIR
        BRU EXIT
$ADST1    PZE
          EOM 030002,2
          SKS 030000
          BRU $-1
          EOM 30060
          PIN *ARRAY
          STA    SVAA
          LDA    =1
          SKE    NCH
          BRU    $+2
          BRU    ADOUT
          EOM 030001,2
          BRX $+1
          SKS 030000
          BRU $-1
          EOM 030060
          PIN *ARRAY
          LDA    =2
          SKE    NCH
          BRU    $+2
          BRU    ADOUT
          EOM    030001,2   CHANNEL 3
          BRX    $+1
          SKS    030000
          BRU    $-1
          EOM    030060
          PIN    *ARRAY
          LDA    =3
          SKE    NCH
          BRU    $+2
          BRU    ADOUT
          EOM    030001,2   CHANNEL 4
          BRX    $+1
          SKS    030000
          BRU    $-1
          EOM    030060
          PIN    *ARRAY
          LDA    =4
          SKE    NCH
          BRU    $+2
```

```
          BRU    ADØUT
          EØM    030001,2  CHANNEL 5
          BRX    $+1
          SKS    030000
          BRU    $-1
          EØM    030060
          PIN    *ARRAY
          LDA    =5
          SKE    NCH
          BRU    $+2
          BRU    ADØUT
          EØM    030001,2  CHANNEL 6
          BRX    $+1
          SKS    030000
          BRU    $-1
          EØM    030060
          PIN    *ARRAY
          LDA    =6
          SKE    NCH
          BRU    $+2
          BRU    ADØUT
          EØM    030001,2  CHANNEL 7
          BRX    $+1
          SKS    030000
          BRU    $-1
          EØM    030060
          PIN    *ARRAY
          LDA    =7
          SKE    NCH
          BRU    $+2
          BRU    ADØUT
          EØM    030001,2  CHANNEL 8
          BRX    $+1
          SKS    030000
          BRU    $-1
          EØM    030060
          PIN    *ARRAY
ADØUT     LDA    SVAA
          BRX CØNT1
          LDX =-1500
          MIN 0200
          ADD =1
          BRR    ADST1
CØNT1     SKN FLAG
          BRR    ADST1
       STA FLAG
       BRU *INTLØC
$ADST2    PZE
          EØM 030002,2
          SKS 030000
          BRU $-1
       EØM 030060
          PIN *ARRAY1
          STA    SVAA
          LDA    =1
          SKE    NCH
          BRU    $+2
          BRU    ADØUT1
          EØM 030001,2
      BRX $+1
```

```
SKS 030000
    BRU $-1
    EOM 030060
    PIN *ARRAY1
    LDA    =2
    SKE    NCH
    BRU    $+2
    BRU    ADOUT1
    EOM    030001,2   CHANNEL 3
    BRX    $+1
    SKS    030000
    BRU    $-1
    EOM    030060
    PIN    *ARRAY1
    LDA    =3
    SKE    NCH
    BRU    $+2
    BRU    ADOUT1
    EOM    030001,2   CHANNEL 4
    BRX    $+1
    SKS    030000
    BRU    $-1
    EOM    030060
    PIN    *ARRAY1
    LDA    =4
    SKE    NCH
    BRU    $+2
    BRU    ADOUT1
    EOM    030001,2   CHANNEL 5
    BRX    $+1
    SKS    030000
    BRU    $-1
    EOM    030060
    PIN    *ARRAY1
    LDA    =5
    SKE    NCH
    BRU    $+2
    BRU    ADOUT1
    EOM    030001,2   CHANNEL 6
    BRX    $+1
    SKS    030000
    BRU    $-1
    EOM    030060
    PIN    *ARRAY1
    LDA    =6
    SKE    NCH
    BRU    $+2
    BRU    ADOUT1
    EOM    030001,2   CHANNEL 7
    BRX    $+1
    SKS    030000
    BRU    $-1
    EOM    030060
    PIN    *ARRAY1
    LDA    =7
    SKE    NCH
    BRU    $+2
    BRU    ADOUT1
    EOM    030001,2   CHANNEL 8
    BRX    $+1
```

```
          SKS    030000
          BRU    $-1
          EOM    030060
          PIN    *ARRAY1
ADOUT1    LDA    SVAA
          BRX CONT2
          LDX =-1500
          SKR 0200
          NOP
          ADD =1
          BRR    ADST2
CONT2     SKN FLAG
          BRR    ADST2
          STA FLAG
          BRU *INTLOC
$INT33    PZE
          STX FLAG
          BRU *INT33
$INT1     SKE =0
       BRU WRIT1
       STX FLAG
       BRU *RETRN
$WRIT1 EOM *03251
       EOM 010001
       POT WDPOT1
       SUB =1
       MIN NREC
       MIN INTLOC
       BRU *RETRN
$INT2 SKE =0
       BRU WRIT2
       BRU INT1+2
$WRIT2 EOM *03251
       EOM 010001
       POT WDPOT2
       SUB =1
       MIN NREC
       SKR INTLOC
       BRU *RETRN
       BRU *RETRN
XSD       OPD    010000000
$CCSET    PZE
          BRM    201SYS
          XSD    KNCH
          XSD    KICY
          XSD    KSG
          BRM    202SYS
          LDA    *KNCH
          STA    NCH
          LDA    *KICY
          STA    ICY
          LDA    =1
          STA    RTC
          LDA    *KSG
          STA    SG
          BRR    CCSET
*         ICY = CYCLE COUNT PARAMETER
*         RTC = REAL TIME CYCLE COUNT
*         NCH = NUMBER OF CHANNELS
NCH       RES    1
```

```
ICY     RES   1
KNCH    RES   2
KICY    RES   2
SVAA    RES   1
RTC     RES   1
KSG     RES   2
SGST    RES   1
SG      RES   1
$CYCL1  PZE
        STA   SVA
        LDA   ICY
        SKE   RTC
        BRU   CYA
        LDA   =1 PROCESS INTERRUPT
        STA   RTC     RESET RTC
        LDA   SVA
        BRM   ADST1
        BRU   *CYCL1
CYA     MIN   RTC             INCREMENT REAL TIME CYCLE
        LDA   SVA
        BRU   *CYCL1
$CYCL2  PZE
        STA   SVA
        LDA   ICY
        SKE   RTC
        BRU   CYB
        LDA   =1
        STA   RTC
        LDA   SVA
        BRM   ADST2
        BRU   *CYCL2
CYB     MIN   RTC
        LDA   SVA
        BRU   *CYCL2
SVA     RES   1
NDATA RES 1
NDATA1 RES 1
NGO RES 2
IDENT RES 1
IDENT1 RES 1
SAVX RES 1
RETRN RES 1
ARRAY RES 1
ARRAY1 RES 1
FLAG RES 1
INTLOC RES 1
INTLO1 DATA INT1
INTLO2 DATA INT2
NREC RES 1
DUMMY RES 1
WDPOT1    RES 1
WDPOT2    RES 1
PNT200  BRM   CYCL1
        BRM   CYCL2
NLAST RES 1
      END
```

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