FRA
79-2

REPORT NO.

PLATE INSTRUMENTED WHEELSETS FOR THE MEASUREMENT OF WHEEL/RAIL FORCES

W. I. Thompson, III

U. S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center
Cambridge, Massachusetts 02142

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL RAILROAD ADMINISTRATION
Office of Research and Development
Washington DC 20590

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
PLATE INSTRUMENTED WHEELSETS FOR MEASUREMENT OF WHEEL/RAIL FORCES

5. Report Date

6. Performing Organization Code
DTS-733

7. Author(s)
W. I. Thompson, III

8. Performing Organization Report No.
DOT-TSC-FRA-79-2

9. Performing Organization Name and Address
U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center
Cambridge, Massachusetts 02142

10. Work Unit No. (TRAIS)
RR919/R9317

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Railroad Administration
Office of Research and Development
Washington DC 20590

13. Type of Report and Period Covered
Final Report
May 1978 - May 1979

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Strain gauge instrumented wheelsets are an important research tool in experimental rail vehicle testing. This report expounds the principle of operation of the instrumented plate type of wheelset which is constructed by the scientifically exact application of strain gauges on the plate region of railroad wheels so that the wheelset is transformed into a sophisticated force transducer. An example of the application of the principles expounded is presented for a locomotive wheelset having wheels with S-shaped plate regions and 40-in. (1016-mm) diameters. The corresponding measurement system that utilizes such instrumented wheelsets is synopsized.

17. Key Words
Rail/Vehicle Dynamics
Locomotives
Strain Gauges
Instrumented Wheelset

18. Distribution Statement
DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8–72) Reproduction of completed page authorized

PREFACE

This report provides background information and technical details on the principle of operation of strain gage instrumented wheelsets used to make wheel/rail force measurements. Recently three instrumented locomotive wheelsets were procured by the National Railroad Passenger Corporation (Amtrak) and the Federal Railroad Administration (FRA). A separate wheel signal processor was procured by the Association of American Railroads (AAR). The above items were designed and manufactured in Sweden by ASEA AB and the Swedish State Railways (SJ) due to their extensive experience with continuously measuring instrumented wheelsets.

The author would like to thank Mr. T. Anderson, Director of the SJ/Rolling Stock Department Laboratory (RSDL) and Messrs. A. Nellgran and S. Ericksson also of RSDL for their hospitality and assistance during his visit to RSDL. Additionally, the author would like to thank Messrs. L.G. Brodin and O. Ewers of ASEA AB and Mr. E.J. Lombardi, Engineer of Tests, for Amtrak for their cooperation and assistance in the development of the wheel/rail force measurement described herein.

CONTENTS

CONTENTS (CONTINUED)

Section Page

APPENDIX

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

a	a geometrical point
Amtrak	National Railroad Passenger Corporation
AAR	Association of American Railroads
AC	alternating current
ASME	American Society of Mechanical Engineers
b	a geometrical point
cm	centimeter
°C	degrees centigrade
dl	change in length
emf	out of balance voltage
E	Young's modulus; a voltage
e_{bc}	electromagnetic force
$F_{\ell f}$	force on a wheel flange in the lateral direction at the wheel/rail interface
$F_{\ell t}$	force on a wheel tread in the lateral direction at the wheel/rail interface
F_t	force on a wheel in the longitudinal direction at the wheel/rail interface
F_v	force on a wheel tread in vertical direction at the wheel/rail interface
F_U	universal force transducer
FRA	Federal Railroad Administration
GE	General Electric Company
GM	General Motors Corporation
Hz	hertz
i	inside

LIST OF ABBREVIATIONS AND SYMBOLS (CONTINUED)

in.	inch(es)
inst.	instrumented
ISA	Instrument Society of America
k	kilo, gage factor, constant
kHz	1000 Hz
ksi	thousands of pounds per square inch
L	left-hand in wheel set, length of wire
ℓ	lateral force
lb	pound
L_f	lateral force at the point of contact of the flange
L_t	lateral force
m	a constant of proportionality, meter(s)
mf	microstrain
mm	millimeters
mA	milliamperes
mV	millivolt
n	a constant of proportionality, an index number
n.d.	no date
N	Newton(s)
o	outside, a geometrical point
ORE	Office of Research & Experiments of the International Railway Union
Q	vertical force (European notation)
r	right-hand rollover ratio, electrical resistance
R_β	resistances

LIST OF ABBREVIATIONS AND SYMBOLS (CONTINUED)

RSDL	Rolling Stock Department Laboratory
SJ	Swedish State Railways
TTC	Transportation Test Center
V	voltage, vertical force
V_1	voltage from vertical force measuring strain gage bridge number 1 on a given instrumented wheel
V_2	voltage from vertical force measuring strain gage bridge number 2 on a given instrumented wheel
Y	lateral force (European notation)
α	coefficient of thermal expansion
β	an index number
δ	differential change
ε	strain
ε_o	strain at initial application of force
ε_∞	strain at limit
μV	microvolt
$\mu\varepsilon$	microstrain
σ	stress
ϕ	angle of rotation of a wheel

1. INTRODUCTION

With the advent of modern measurement techniques, the world's railroads have been undertaking detailed engineering tests in which the forces at the wheel/rail interface have been measured with various degrees of accuracy and precision. An accurate value of the dynamic force at the wheel/rail contact is an essential measurement for the proper understanding of the behavior of vehicles and the track on which they run. The wheel/rail contact forces depend on the wheel/rail contact geometry and the creepage-creep force relationships (Wickens and Gilchrist, 1977). It is the input force to the suspension which has an influence on ride quality, ability to negotiate curves, wheel-tread wear, and derailment. It is also the force transmitted to the track, which can damage rail ends, propagate rail flaws, produce rail wear, loosen fastenings, produce corrugations, weaken ballast and cause many other kinds of damage and problems.

The force which occurs between a wheel and rail can be resolved into three components at right angles to each other, namely, a vertical force, a lateral force in a direction towards or away from the flange, and a longitudinal force - parallel to the rail (see Figures 1 and 2). Note that when a wheelset moves in the lateral direction and the wheel flange approaches the rail, two contact points between wheel and rail are usually assumed, one on the wheel tread and the other on the flange. At the contact point on the tread, vertical force and the creep forces in both longitudinal and lateral directions are transmitted and at the point on the flange only the side thrust is transmitted (Kunieda, 1970).

Wickens, A.H. and A.O. Gilchrist, (1977), Vehicle dynamics - a practical theory, Railway Engineer, 2, (4), 26-34.

Kunieda, M., (1970), Theoretical study on the side thrust of truck wheels running on curves, Q. Rpt. Railway Tech. Res. Inst., 11, (2), 105-108.

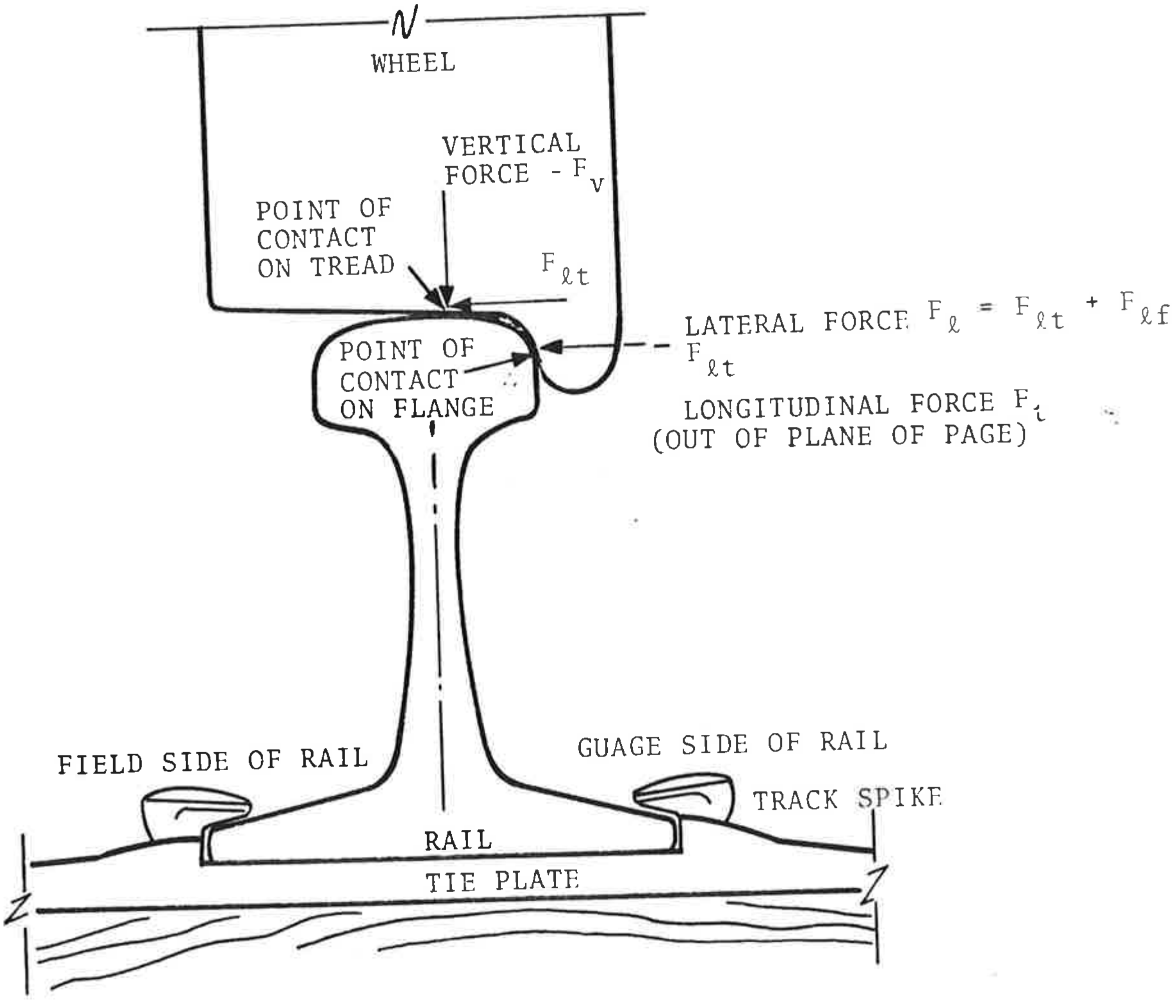


FIGURE 1. SCHEMATIC DIAGRAM OF THE WHEEL/RAIL INTERFACE REGION

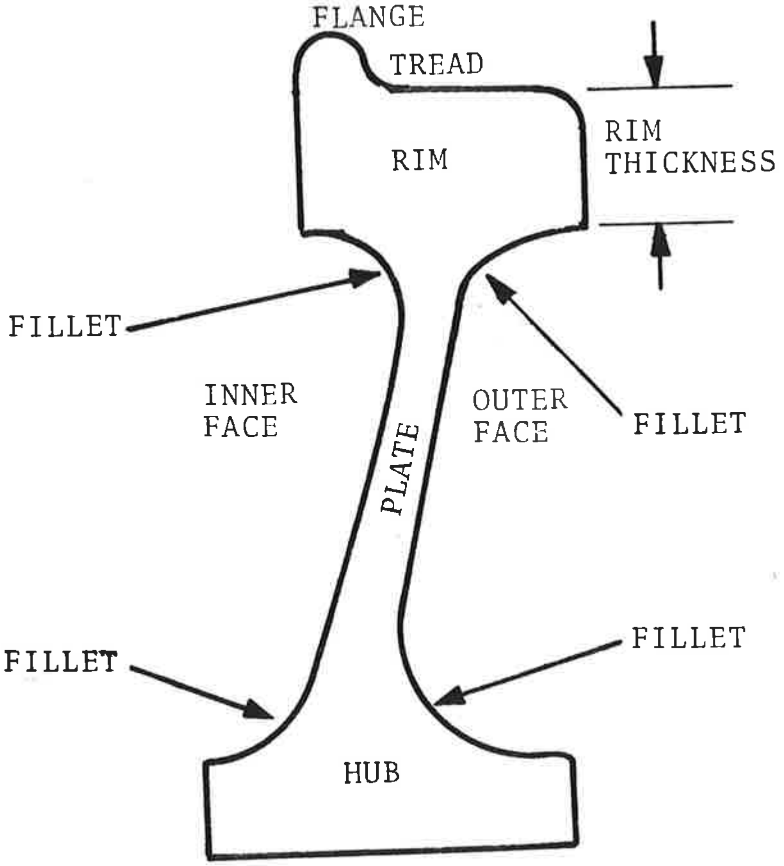


FIGURE 2. DIAGRAM OF A CROSS SECTION OF A RAILROAD WHEEL IDENTIFYING THE VARIOUS PARTS

During incipient flange climbing, however, both the vertical and lateral loads are transferred through the contact point on the flange.

Vertical forces are due to the vehicle static weight, dynamic forces from wheel irregularities and the response of the vehicle and track to track geometry irregularities. Lateral forces are produced from the vehicle response to track geometry irregularities, components of longitudinal train-action forces and external disturbances such as wind forces, self-excited hunting motions, and creep and flange forces necessary to guide the vehicle through curves. Longitudinal forces are caused by wheel/rail creep, traction, and braking.

Experience and theoretical research point towards an increase in the risk of derailment of an axle proportional to the ratio of the lateral (guiding) component ($F\ell_f$) to the normal (load) component (F_v) of the force applied to the rail by this wheel. Because this ratio is expressed in different ways by various administrations around the world, Appendix A presents a discussion of this important vehicle dynamic parameter.

Ideally, we would wish to measure these forces at the wheel/rail contact point or at a point very close to it. The simpler practice of measuring forces in the suspension takes place at a position well removed from the place of occurrence and even if modified by the addition of a mass times acceleration term, it still leaves much to be desired as a useful signal. In particular, it is only possible to measure the total lateral force between wheelset and track in this case, and, in consequence, vital data with respect to derailment tendency and wheel flange and rail sideware are not available. If such data is to be obtained, then it is essential to measure individual wheel forces.

The difficulties with instrumented wheelsets involve obtaining a relatively continuous measurement; uncoupling vertical, lateral and longitudinal force contributions to the strains; and reliably carrying the electrical measurements through slip rings, or some type of telemetry device, to onboard recorders.

This report will present a brief history and expound the principle of operation of plate instrumented wheelsets. An example of the principles expounded for a locomotive wheelset having wheels with S-shaped plate regions and 40-in. (1016-mm) diameters is provided along with a summary of a complete measurement system employing such instrumented wheelsets.

2. BRIEF HISTORY

The basic component of instrumented wheelsets is the electrical resistance strain guage introduced into the United States in 1939 by Ruge and Simmons (Hearn, 1971). In 1946 M. F. Verigo in the Soviet Union suggested the introduction of a continuous recording of the forces exerted by the wheel on the track, by measuring the vertical and horizontal components of the wheel/rail interaction forces through the use of the stressed state of the wheel plate or disc. (Shafranofskii, 1965). The Japanese National Railway (JNR) has been developing and improving techniques to measure wheel loads since 1952 (Konishi, 1967). They have emphasized the performance of the spoked wheel over the plate instrumented wheel as the basis of an instrumented wheel set based on the claim that the spoked wheel offers better control of sensitivities and load isolation. The Office of of Research and Experiments (ORE) of the International Railway Union (UIC) has also sponsored research on both spoke- and plate-instrumented wheelsets.

The basic technique for measuring wheel/rail interaction forces makes use of strain gauges placed on the plate or spokes of a railroad wheel. These gauges transduce the strain in the wheel produced by the wheel/rail interaction forces into proportional electrical signals which can then be recorded. The strain gauge patterns on the wheel have a narrow influence zone about the wheel/rail contact patch (plus or minus a few centimeters) with a

---

Hearn, E. J. (1971), Strain Gauges, Merrow Publ. Co., Ltd., Watford, England.

Shafranovskii, A. K. (1965), Continuous Recording of Vertical and Lateral Forces of Interaction Between the Wheel and a Rail, Central Scientific Research Institute, Ministry of Rolling Stock, Moscow. (In Russian)

Konishi, S. (1967), Measurement of loads on wheel sets, Japanese Railway Engineering, 8, (3), 26-29.

nominal maximum gain as the gauge pattern passes through the plane of the force vector. Therefore, each wheel-mounted gauge pattern sees a vertical or lateral force sample once (or twice) per revolution.

The history of instrumented wheelsets is open to different interpreations, but the technique became well-known after being publicized in the papers by Olson and Johnsson (1959, 1960). Since then there have been elaborations and improvements primarily in the area of signal conditioning. This history will deal only with plate instrumented wheelsets.

Olson and Johnsson established that the radial strains of the wheel plate are very sensitive to lateral forces and almost insensitive to vertical forces. This enabled them to work out a method of continuous recording of lateral (horizontal transverse) forces acting between the wheel and rail, by measuring the radial strains of the wheel plate, and to design instruments for statistical recording of average values of the forces.

In 1962 the Electro Motive Division (EMD) of the General Motors Corporation (GM) constructed a plate instrumented locomotive wheelset which provided a lateral force signal proportional to the average strain in the wheel plate (Koci and Marta, 1965). Vertical wheel load information was obtained from gauges mounted

---

Olson, P. E. and S. Johnsson, (1959), Lateral forces between wheel and rail, Glas. Ann., 83, (5), 153-161. (In German)

Olson, P. E. and S. Johnsson, (1960), Lateral forces between wheels and rails - an experimental investigation, ASME Paper No. 60-RR-6, also in Anthology of Rail Vehicle Dynamics, Vol. III, Axles, Wheels and Rail-Wheel Interaction, S. G. Guins and C. E. Tack, Editors, American society of Mechanical Engineers, New York, pp. 253-261.

Koci, L. F. and H. A. Marta, (1965), Lateral loading between locomotive truck wheels and rail due to curve negotiation, ASME Paper No. 65-WA/RR-4, also in Anthology of Rail Vehicle Dynamics, Vol. III, Axles, Wheels and Rail-Wheel Interactions, S. G. Guins and C. E. Tack, Editors, American Society of Mechanical Engineers, New York, pp. 119-129.

in a whole drilled through the wheel plate. This arrangement provided a spike signal proportional to the vertical wheel load once per revolution. This wheelset was regauged in 1968 and used until 1972.

Russian experiments have reported using a number of radially oriented strain gauges, equally spaced, but wired into a common bridge to sense either vertical or lateral loads (Shafranovskii, 1965).

A new locomotive wheelset was prepared by EMD in 1973. This new wheelset utilized new gauge locations to minimize the influence of wheel/rail lateral orientation effects on the lateral output and some new wiring arrangements. The strain gauge bridge was configured in such a way that its output was sensitive to symmetrical bending. More detailed information on the EMD wheelsets is provided by Modransky et al. (1979).

In 1973 the FRA contracted with the Association of American Railroads (AAR) to instrument all four CK-36 cast steel wheels of a Barber S-2 100-ton freight car truck to measure the lateral and vertical forces. (Anon. 1975). The wheelsets measured lateral forces continuously but the vertical load measurement was limited to a spatial resolution of one quarter of the wheel circumference.

The Canadian National (CN) Research Center developed an instrumented wheelset using standard disc wheels, but they used cast wheels instead of wrought wheels. This was done to obtain a wheel thickness that is uniform with 1/16 of an inch, which is considerably better than wrought wheels (Prause and Harrison, 1975).

Modransky, J., W. J. Donnelly, S. P. Novak and K. R. Smith, (1979), Instrumented locomotive wheels for continuous measurements of vertical and lateral loads, ASME Paper No. 79-RT-8, American Society of Mechanical Engineers, New York.

Anon. (1975), Instrumentation for measurement of forces on wheels of rail vehicles, Rpt. No. FRA-ORD&D-75-11, Association of American Railroads, Chicago IL and ENSCO, Inc., Springfield VA (PB-247154).

Prause, R. H. and H. D. Harrison, (1975), Data analysis and instrumentation requirements for evaluating rail joints and rail fasteners in urban track, Rpt. No. DOT-TSC-UMTA-75-2, Battelle Columbus Laboratories, Columbus OH.

Both General Electric (Dolecki and Hartzell, 1974) on the U30C locomotive and EMD on the SPD-40 locomotive have utilized a number of radially oriented strain gauges in individual bridges sensed only within the narrow arc of maximum sensitivity. On both of these locomotives, only a single instrumented wheelset was utilized, usually placed as the lead axle of the leading or trailing truck of the locomotive unit.

In 1976 Amtrak evaluated the ASEA-built Rc4A locomotive on American track using two of strain-gauged wheelsets provided by SJ on one truck to provide analog signals of single-wheel vertical and lateral wheel/rail forces, and both single-wheel and total-truck (one rail) lateral to vertical force ratios.

The FRA contracted with ENSCO, Inc. to construct an instrumented locomotive wheelset where each wheel contained two vertical and two lateral bridges. Vertical bridges were composed of strain guages installed in the top and bottom of holes drilled through the wheel plate as in the EMD wheelsets (ENSCO, 1977). This wheelset was used in the tests of an Amtrak SPD-40F train consist on Chessie system track in 1977 (Tong et al. 1979).

In 1977 Amtrak and the FRA procured three instrumented locomotive wheelsets from ASEA AB. ASEA AB teamed with the Swedish State Railways to produce the instrumented locomotive wheelsets which are described in Chapter 4 of this report. The continuous vertical force is produced by combining two triangular wave shapes electronically. (Ericksson and Nellgran (1978). These

---

Dolecki, E. A. and C. E. Hartzell, (1974), Operating and ride qualities, three axle, floating bolster truck, GE Tech. Infor. Series, DF74LC2690, General Electric Co., Erie PA

ENSCO, (1977), SPD-40F/E-8 locomotives - test results report: dynamic performance testing, Rpt. No. DOT-78-10, Vol. II, ENSCO, Inc., Engineering Test & Analysis Div., Alexandria VA.

Tong, P., R. Brantman, R. Greif and J. Mirabella, (1979), Tests of the Amtrack SDP-40F train consist conducted on Chessie System track, Rpt. no. DOT-TSC-FRA-79-14, DOT/Transportation Systems Center, Cambridge MA.

Ericksson, S. and A. Nellgran, (1978), Improved signal conditioning methods for measuring the vertical forces at the wheel/rail interface, ZEV-Glas. 102, (5), 143-146.

wheelsets were used in the recently concluded Perturbed Track Tests conducted by the FRA in November-December 1978 at the Transportation Test Center (TTC) in Pueblo, Colorado.

Burada et al. (1978) reported on some experimental investigations where the vertical force measuring snesitivity was increased by creating small "dummy spokes" by drilling the plate of the wheel close to the rim, where assembly stresses are small.

Figure 3 illustrates an evolutionary development of plate instrumented wheelsets put together from published literature. Generally, as one proceeds to the 1970's, the accuracy of the wheelsets as transducers increases because new electronic techniques make improved signal processing, sometimes on the wheelset itself, possible.

Most recently Modransky et al. (1970) have reported on the latest instrumented locomotive wheelsets produced by EMD which can continuously measure lateral and vertical wheel/rail forces. The technique utilizes strain gauges applied to a typical locomotive wheel plate to generate sinusoidal waveforms which are electronically combined to provide continuous signals proportional to the lateral and vertical components of the net wheel loading.

Burada, C., M. Buga, L. Nailescu and A. Popistas, (1978), Possibilities to improve sensitivity of the methods for the Q-force measuring by means of spoke wheels and disk wheels, pp. 3-4-1 through 3-4-18 in Proceeding of the Sixth International Wheelset Congress, Colorado Springs CO, October.

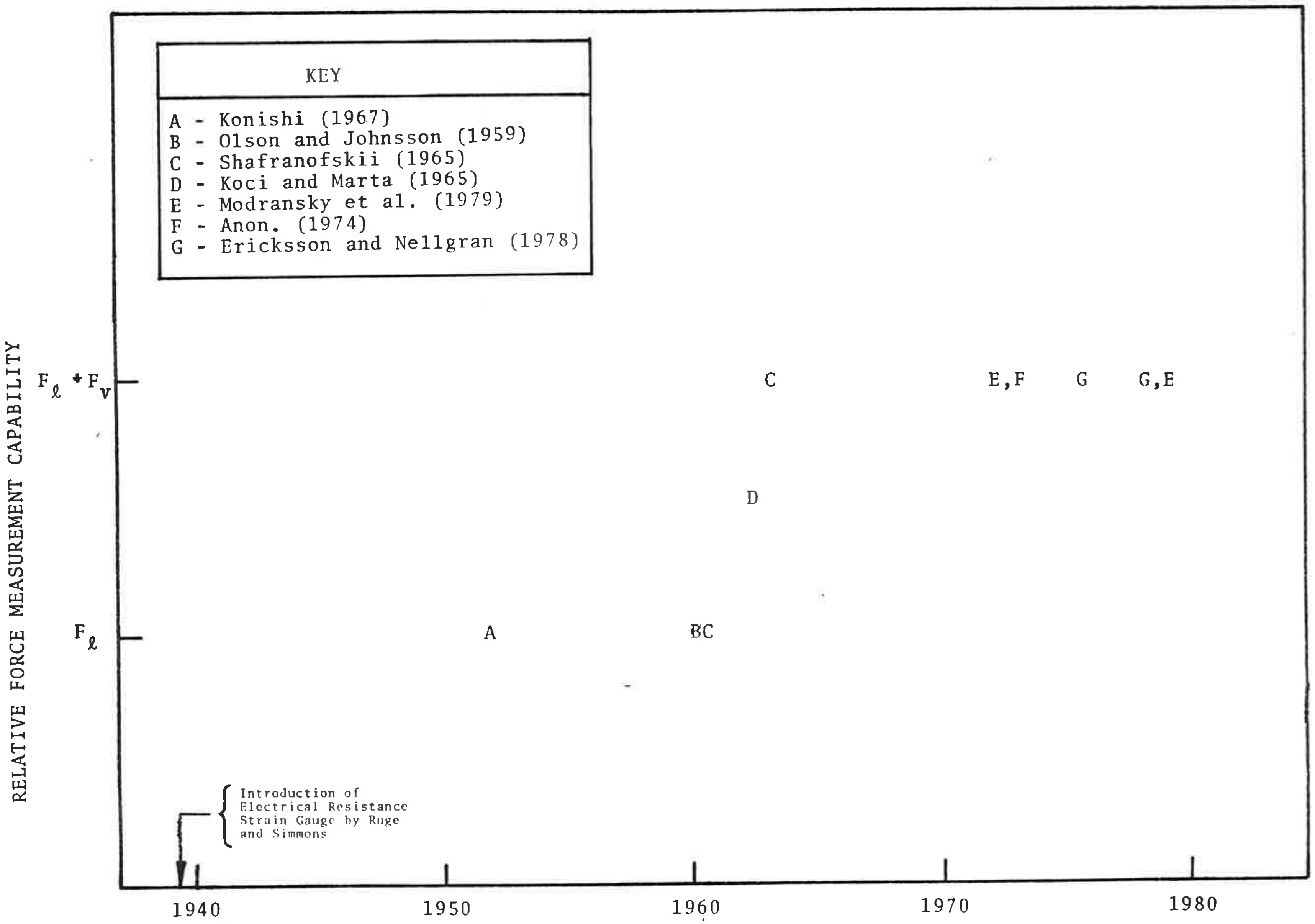


FIGURE 3. DIAGRAM OF THE EVOLUTIONARY DEVELOPMENT OF STRAIN GAUGE INSTRUMENTED WHEELSETS

3. PRINCIPLE OF OPERATION

3.1 STRESS/STRAIN RELATIONSHIPS

The use of strain gage instrumented wheelsets is based on standard techniques used in experimental stress analysis (Holister, 1967). When a force is applied to a structure, the structure will deform in a manner dependent on its shape, the type of material from which it is constructed and the manner in which the force is applied. This deformation is called the strain (ε). Strain is usually expressed as a ratio of the change in dimension ($d\ell$), to the original dimension and, since we are only concerned with strain in a length of wire, (ℓ), we may write

$$\varepsilon = d\ell/\ell \tag{1}$$

where $d\ell$ is the change in length. Therefore, strain is dimensionless and because of the relatively small ratio is usually expressed as microstrain ($\mu\varepsilon$). Thus

$$1\ \mu\varepsilon = d\ell/\ell \times 10^6 \tag{2}$$

For the application here, the applied force per unit area, the stress, (σ) will always be within the elastic limit of the materials so that the materials will obey Hooke's law and the ratio of stress/strain is a constant denoted by E, Young's modulus. Thus we may write

$$\sigma/\varepsilon = E \text{ or } \sigma = E\varepsilon \tag{3}$$

that is, stress is proportional to strain. The units of the proportionality constant (E) will be those of stress (i.e., lb/in.^2 or N/m^2) because strain is dimensionless.

Holister, G. S. (1967), Experimental Stress Analysis: Principles and Methods, Cambridge Univ. Press, Cambridge.

As an example for steel below the limit of proportionality the modulus of elasticity is about 3 x 10^7 lb/in.^{2} According to Hooke's law this means that when steel is subjected to a strain of, for example, p.1% (ε = 10^{-3}), the corresponding stress in the steel is: $\sigma = \varepsilon$ = (3 x 10^7) (10^{-3}) = 3 x 10^{-4} lb/in.^{2} Since the electrical resistance of the strain gauge is proportional to the stress, the strain gauge can be regarded as a stress-measuring device and can be calibrated to give stress readings for any particular material.

3.2 ELECTRICAL RESISTANCE STRAIN GAUGE

The electrical-resistance strain gauge was introduced in 1939 by Ruge and Simmons. It operates on the principle, discovered in 1856 by Lord Kelvin, that when an electrical conductor is strained its resistance varies in proportion to the strain, extensional strains producing for most metals an increase in resistance, compressional strains producing a decrease.

It is found that the basic equation relating change of resistance (R) of a wire strain gauge of length (ℓ) is

$$\frac{dR}{R} = k \frac{d\ell}{\ell} \tag{4}$$

where $d\ell/\ell$ is the longitudinal strain and k is the 'gauge factor' or strain sensitivity factor for a given gauge. For the gauges used here, k is approximately 2.

If a conducting wire is bonded to a structure so that strains experienced by the structure are transmitted to the wire, a measure of the wire's resistance change will give us an indication of the surface strain in the direction of the wire.

3.3 BASIC WHEATSTONE BRIDGE

To measure the change in resistance in a strain gauge we make use of a basic Wheatstone bridge shown in Figure 4, where R_1, R_2, R_3 and R_4 represent the resitances of strain gauge numbers 1-4,

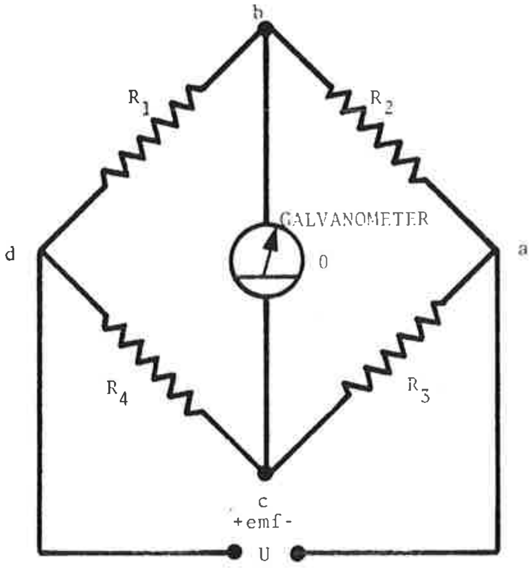


FIGURE 4. BASIC WHEATSTONE BRIDGE CIRCUIT FOR MEASRUING RESISTANCE CHANGES

respectively. If R_1 is an active gauge, then readings of R_1 under 'load' and 'no-load' conditions will give us a measure of δR_1 and hence:

$$\varepsilon = \frac{1}{k} \frac{\delta R_1}{R_1} \tag{5}$$

where ε is the strain in R_1 and k is the gauge factor.

By carrying out a detailed circuit analysis it can be shown that the out-of-balance voltage appearing across the galvanometer terminals (e_{bc}) is approximately proportional to the gauge axial strain (ε) (assuming an infinite resitance across b-c). The equation is

$$e_{bc} = \left[kU \frac{m}{(1+m)^2} \right] \varepsilon \tag{6}$$

where m is defined by $R_2 = mR_1$ and $R_3 = nR_2 = mnR_1$ and $R_4 = nR_1$. Thus the out-of-balance voltage (e_{bc}) is approximately proportional to the gauge strain (ε).

Without going into details, it is generally true that for maximum bridge sensitivity m = 1 and $R_1 = R_2 = R_3 = R_4$ is the case used in most bridge circuits.

Thus for one active gauge (Quarter-bridge)

$$e_{bc} = \frac{kU}{4}\,\varepsilon \quad \text{or} \quad \varepsilon\ \frac{4\,e_{bc}}{kU}\ . \tag{7}$$

Considering a general expression for the bridge output voltage e_{bc} when $R_1 = R_2 = R_3 = R_4$ and

R_1 changes to $R_1 + \delta R_1$

R_2 changes to $R_2 + \delta R_2$

R_3 changes to $R_3 + \delta R_3$

R_4 changes to $R_4 + \delta R_4$

we have, from (7)

$$e_{bc} = \frac{U}{4}\left[\frac{\delta R_1}{R_1} - \frac{\delta R_2}{R_2} + \frac{\delta R_3}{R_3} - \frac{\delta R_4}{R_4}\right] \tag{8}$$

for the circuit illustrated in Figure 4.

3.4 SPECIAL CIRCUITS

3.4.1 Half-Bridge Circuit for Measurement of Bending Strains Only

By combining gauges in various configurations it is possible to measure various types of strains. Part A of Figure 5 shows strain gauges arranged in a half-bridge configuration for the measurement of bending strains only. Gauges R_1 and R_2 are mounted on opposite sides of the material, have equal resistances (i.e., m = 1), and are connected as shown.

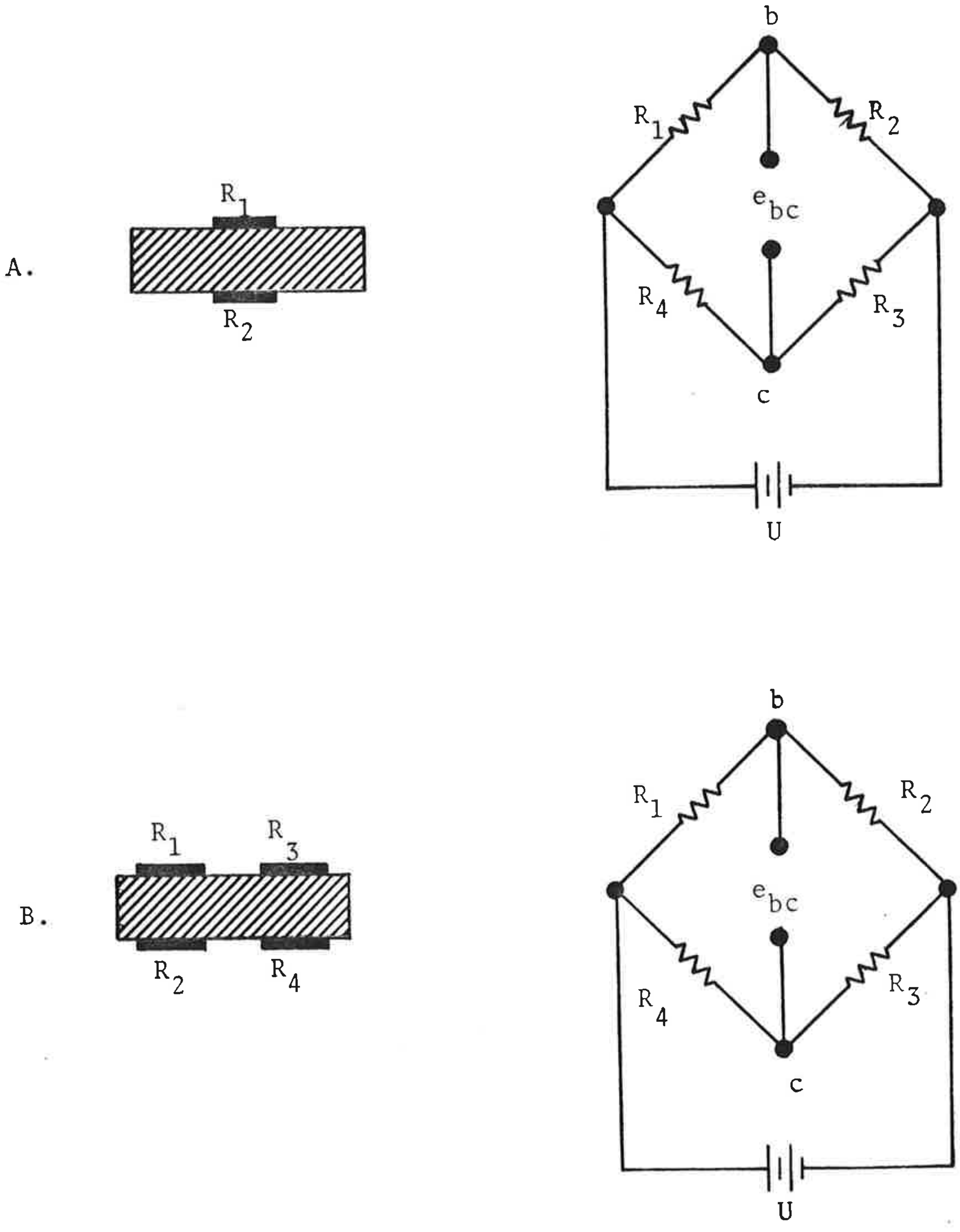


FIGURE 5. CIRCUIT DIAGRAMS FOR MEASURING BENDING STRESSES: (A) HALF-BRIDGE, (B) FULL BRIDGE

Under load conditions it can be shown using (8) that

$$e_{bc} = k \frac{U}{2} \varepsilon_m \text{ or } \varepsilon_m = \frac{2}{kU} e_{bc} \qquad (9)$$

where ε_m is the axial strain. Thus we have doubled the sensitivity of the normal bridge in which R_2 is inactive (7). This type of circuit is used in vertical force measuring bridges described in Section 3.7.

3.4.2 Full-Bridge Circuit for Measurement of Bending Strains Only

Part B of Figure 5 shows strain gauges arranged in a full-bridge configuration for the measurement of bending strains only. Gauges R_1 and R_2, and R_3 and R_4 are mounted on opposite sides of the material, have equal resistances (i.e., m = 1), and are connected as shown.

Under load conditions it can be shown using (8) that

$$e_{bc} = kU \varepsilon_m \text{ or } \varepsilon_m = \frac{1}{kU} e_{bc}. \qquad (10)$$

Thus we have achieved a sensitivity four times the normal bridge circuit.

This type of circuit is used in the lateral force measuring bridges described in Section 3.7.

3.5 STRAIN DISTRIBUTION ON WHEEL PLATES

There has been some interest in the theoretical prediction and measurement of the strain distributions on railroad wheel plates under various loading conditions. Since many of the calculation procedures involve proprietary information, they are not generally available to the public. Recently, however, some studies in predicting surface strain stresses have become available

and reported by Johnson and Yeung (1977) so that the following brief summary has been made possible. This information should help to understand better the principle of operation of instrumented wheelsets.

Figure 6 shows predictions of surface stresses from a 32,000 lb (145 kN) vertical wheel load for a two-wear wrought steel (J36) wheel. The stresses are directed along the intersection of a radial plane with both the inside and outside plate surfaces (see Figure 2) of the wheel. Part A of Figure 6 shows data for the radial cross section of the wheel containing the wheel/rail contact point (0° position) and Part B of Figure 6 shows data for the rest of the plane containing the wheel/rail contact point on the opposite side of the hub (180° position). The wheel plate stresses reach their local maxima and minima at these two positions: the stress at any given point of the wheel has a cyclic character as the wheel rotates as is indicated by the curve in Figure 7 which happens to be for a railroad wheel with a different shaped plate region.

The position of application of the vertical load on the tread of the wheel also affects the surface stress in the J36 wheel. Figure 6 shows stress predictions for the vertical load applied at the tape line and at positions 1-in. (2.54-cm) in and the 1-in. (2.54-cm) out from the tape line. The largest cyclic variation occurs on the inside of the wheel at the rim fillet where for the 1-in. (2.54-cm) in application of load the cyclic variation is from -7.5 to +0.9 ksi. A stress range almost as large occurs at the outside hub fillet for the 1-in. (2.54-cm) out application of load where the cyclic stress range is from -5.6 to +2.2 ksi.

The S-shaped wheel plate used in the present wheelset was selected because there is no measurable variation with the lateral position of application of the vertical load.

Johnson, M.R. and K. S. Yeung, (1978), Application of finite element analysis to the study of railroad wheel failure phenomena, pp. 387-403 in Track/Train Dynamics & Design: Advanced Techniques, Edited by G. J. Moyar, W. D. Pilkey and B. F. Pilkey, Pergamon Press, New York

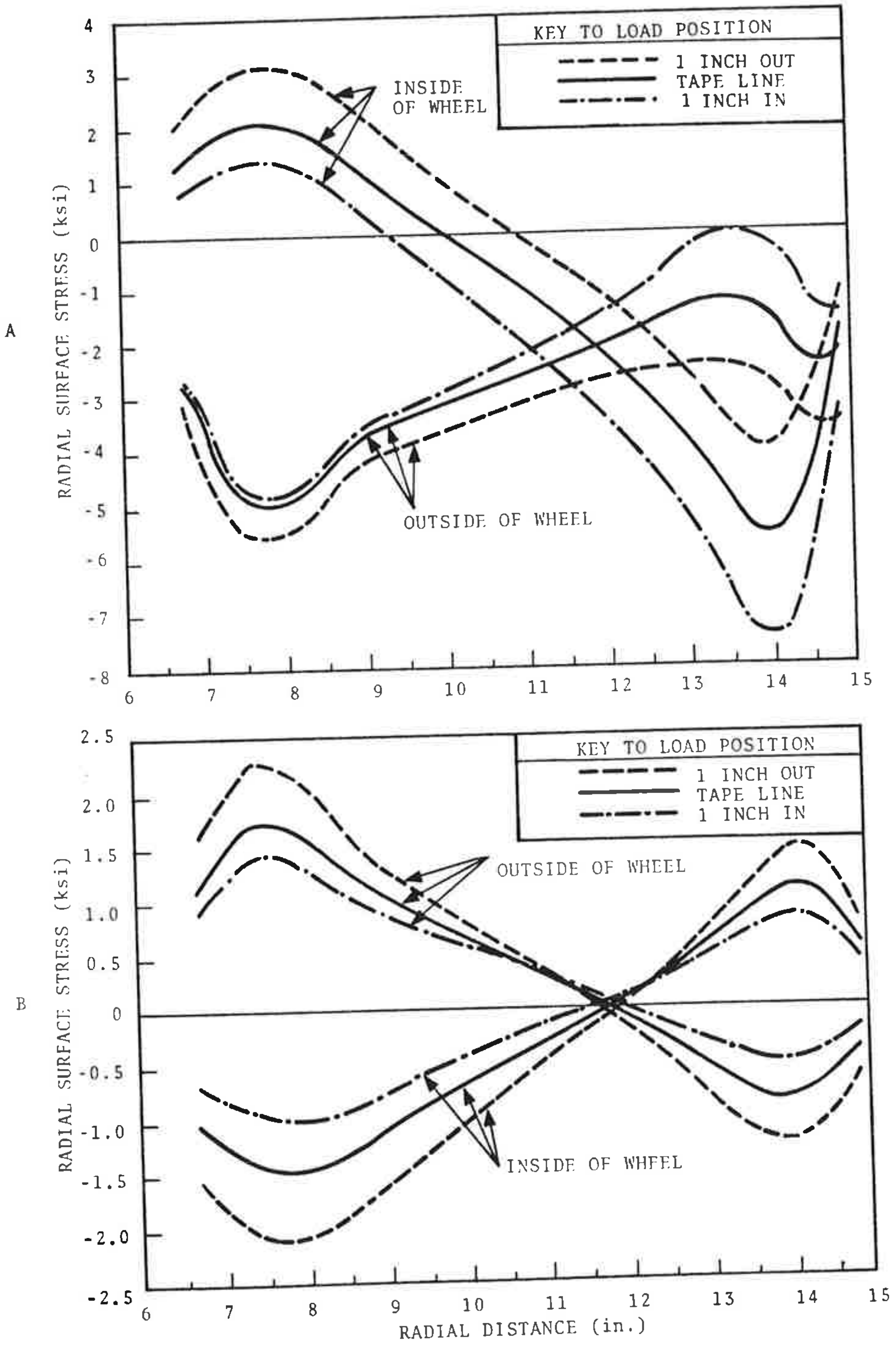


FIGURE 6. CALCULATED RADIAL SURFACE STRESS ON A TWO-WEAR 36-IN. (914.4-mm) DIAMETER RAILROAD WHEEL RESULTING FROM A 32,000 LB (145 kN) VERTICAL LOAD IN THE (A) 0° RADIAL PLANE - THE PLANE OF LOAD APPLICATION: AND THE (B) 180° RADIAL PLANE - THE PLANE OPPOSITE LOAD APPLICATION (AFTER JOHNSON AND YEUNG, 1978)

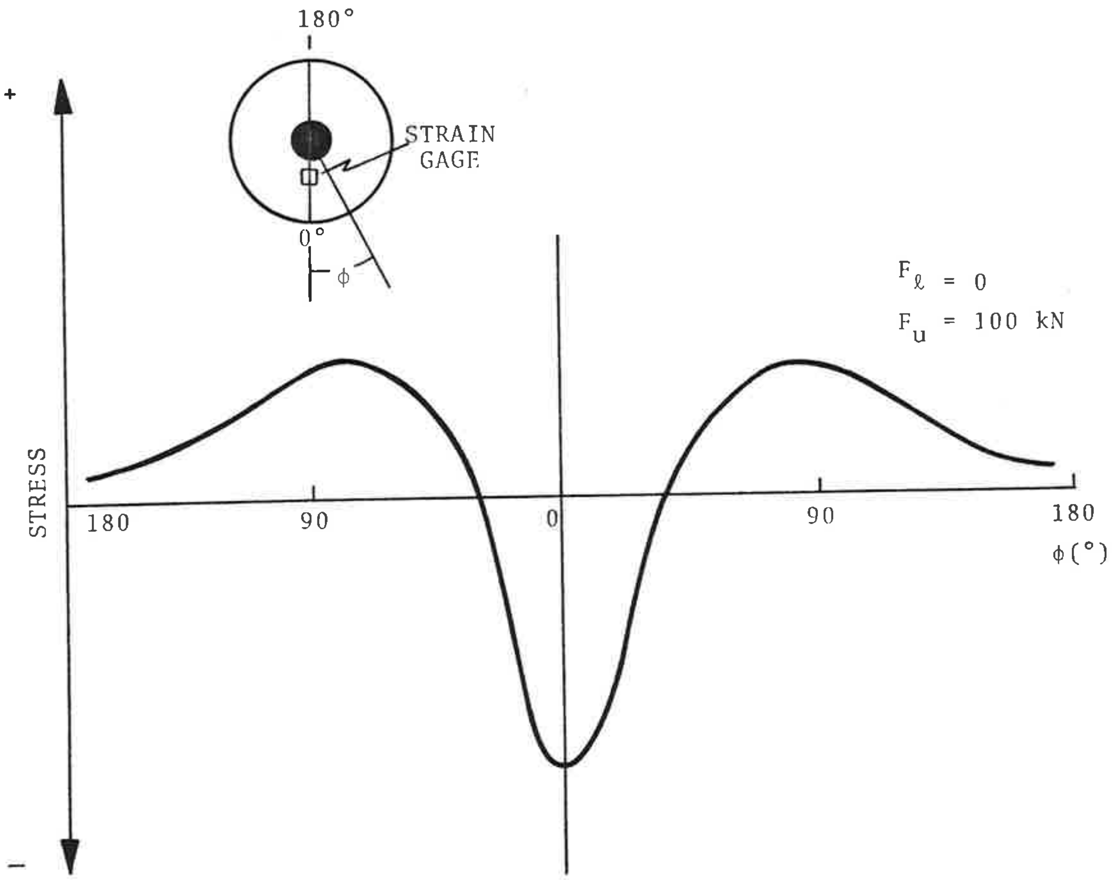


FIGURE 7. TYPICAL CALCULATED ANGULAR STRAIN DISTRIBUTION FOR A RAILROAD WHEEL WITH AN S-SHAPED PLATE REGION AS WOULD BE EXPERIENCED BY ONE STRAIN GAGE ON A POSITION OF THE INSIDE OF THE WHEEL PLATE WITH NO LATERAL LOAD AND A 100 kN (22,000 LB.) VERTICAL LOAD

Figure 8 shows similar predictions for the effects of a 10,000 lb (44.5kN) lateral load acting against the flange of the wheel. The figure shows stress data for both the 0° and 180° radial plane. In this case, the largest stress occurs in the hub fillet region.

3.6 STRAIN SEARCH TECHNIQUE

The fundamental technique which allows the standard wheel to be used is the strain search technique illustrated in Figure 9. A series of strain gauges are mounted along a radial line on both the inside and outside surfaces of the wheel. A set of measurements are made for several combinations of vertical and lateral load. The curves produced from these measurements quickly locate the radius of a circle which produces a minimum amount of crosstalk between the vertical and lateral force measurements. Whether this location actually occurs on the inside or outside of the wheel depends on the particular wheel configuration.

3.7 INSTRUMENTED WHEEL PLATES

The goal of the wheel/rail force measurement system described herein is to provide accurate continuous signals representing the vertical and lateral forces being experienced at the wheel/rail interface. This is difficult to achieve because, as described above, there is an inherent variation in the signal strength of any wheel mounted strain gauge bridge as a function of wheel position even though the wheel load is constant. This occurs because the gauges have maximum sensitivity when they are positioned on the radial line between the center of the wheel and the wheel/rail contact point. A symmetrical bridge on a diametrical line will provide a full load signal twice per revolution but the signal strength will diminish rapidly as the gauge line is rotated away from the wheel/rail contact point. At some intermediate position, the signal goes through zero so that each succeeding peak is opposite in sign as was shown in Figure 7.

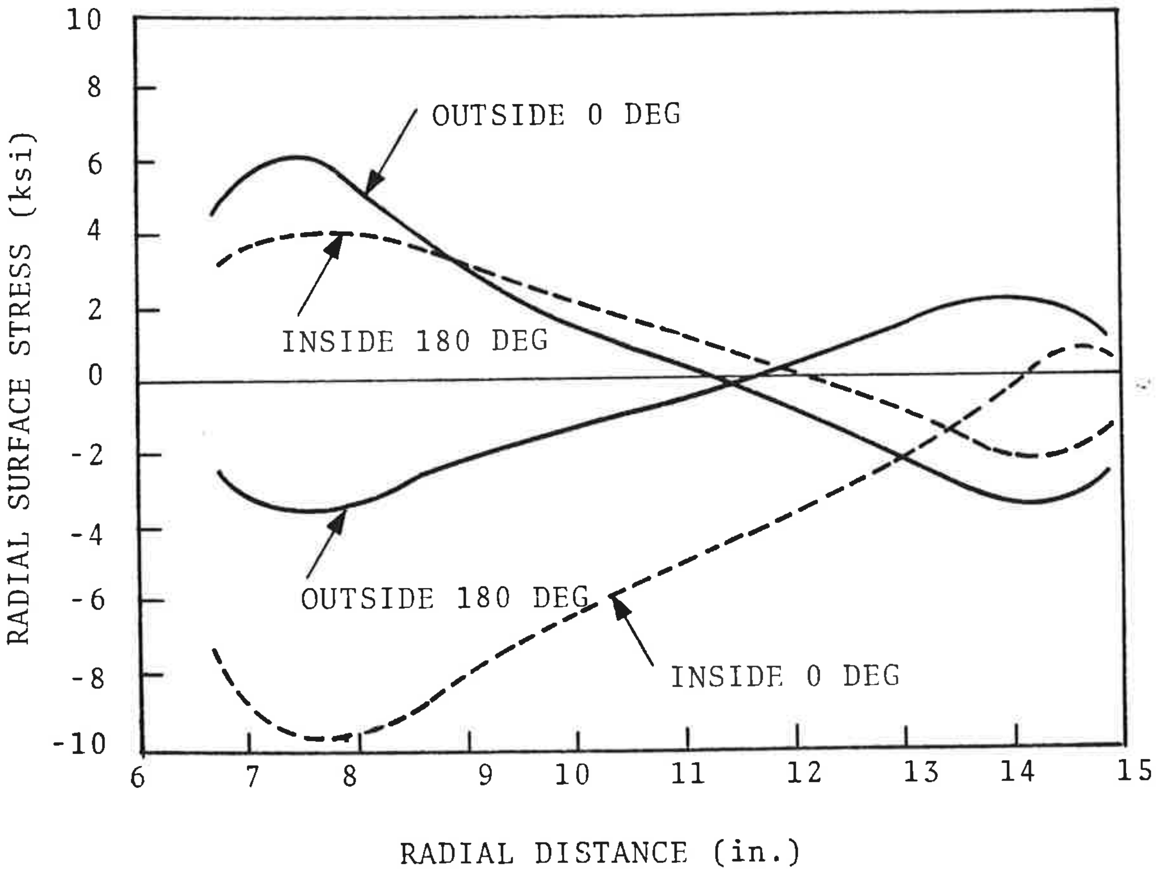


FIGURE 8. CALCULATED RADIAL SURFACE STRESS ON A WHEEL PLATE RESULTING FROM A 10,000 LB (44,5 kN) LATERAL LOAD AGAINST THE FLANGE ON A TWO-WEAR 36-IN. (914.4-mm) DIAMETER WHEEL (AFTER JOHNSON AND YEUNG, 1978)

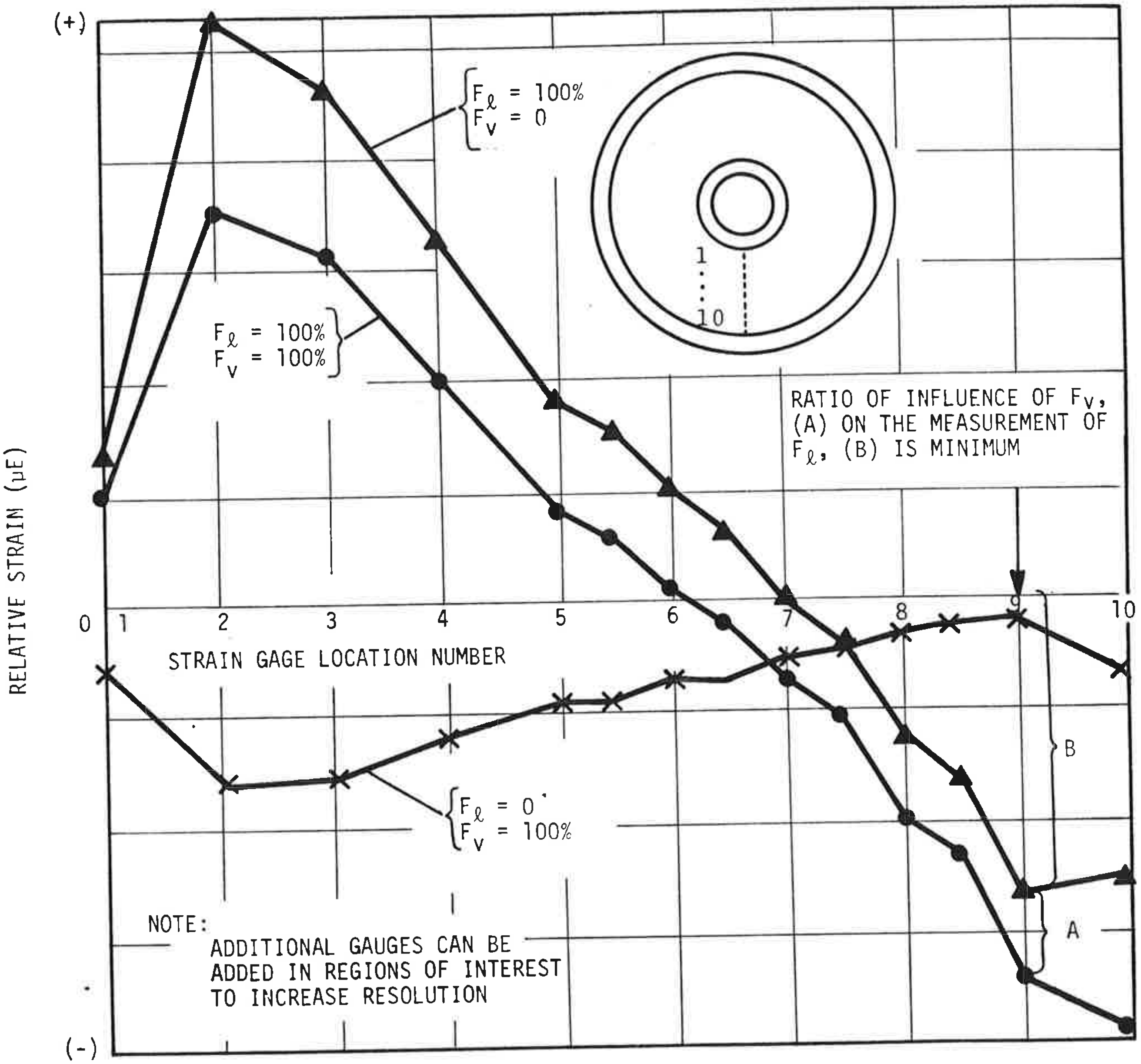


FIGURE 9. ILLUSTRATION OF THE STRAIN SEARCH TECHNIQUE FOR A RAILROAD WHEEL WITH A SOLID PLATE

The output of a bridge containing several gauges distributed around the wheel will have less variation with rotation. Some bridge arrays will provide a nearly constant output over a complete wheel revolution. This type of bridge will show some change in sensitivity when the individual strain gauges rotate through a line between the center of the wheel and the wheel/rail contact point.

Thus, the strain gauge placement techniques described in Section 3.4 are utilized to achieve an optimum bending stress sensitivity for the strain gauge bridges. The placement of the bridges is chosen to provide as nearly a continuous output signal as possible.

3.8 VERTICAL LOAD BRIDGES

Sensitivity is increased in the vertical load measuring bridges (Figure 10) by using half-bridge circuits and placing the appropriate strain gauges on opposite sides of the wheel plate. Continuity of signal output is partially achieved by orientating pairs of gauges symmetrically on a diametrical line. That is, two gauges (for example R_{13} and R_{17}) are placed on one side of the wheel plate and two gauges (for example R_{14} and R_{18}) are placed on the opposite side at the same radial positions. There are then several such quadruple sets distributed symmetrically around the wheel and the two vertical bridges are oriented 45° apart. Despite this arrangement, it is necessary to combine the signals from two vertical load measuring bridges in an electronic wheel signal processor to produce the desired continuous output signal. Figures 11A and 11B illustrate the arrangement used in the present plate instrumented wheelsets. Ericksson and Nellgran (1978) discuss the improved signal conditioning methods.

3.9 LATERAL LOAD BRIDGES

The sensitivity is increased in the lateral load bridges by using full-bridge circuits and placing the appropriate gauges on opposite sides of the wheel plate. The goal of a continuous

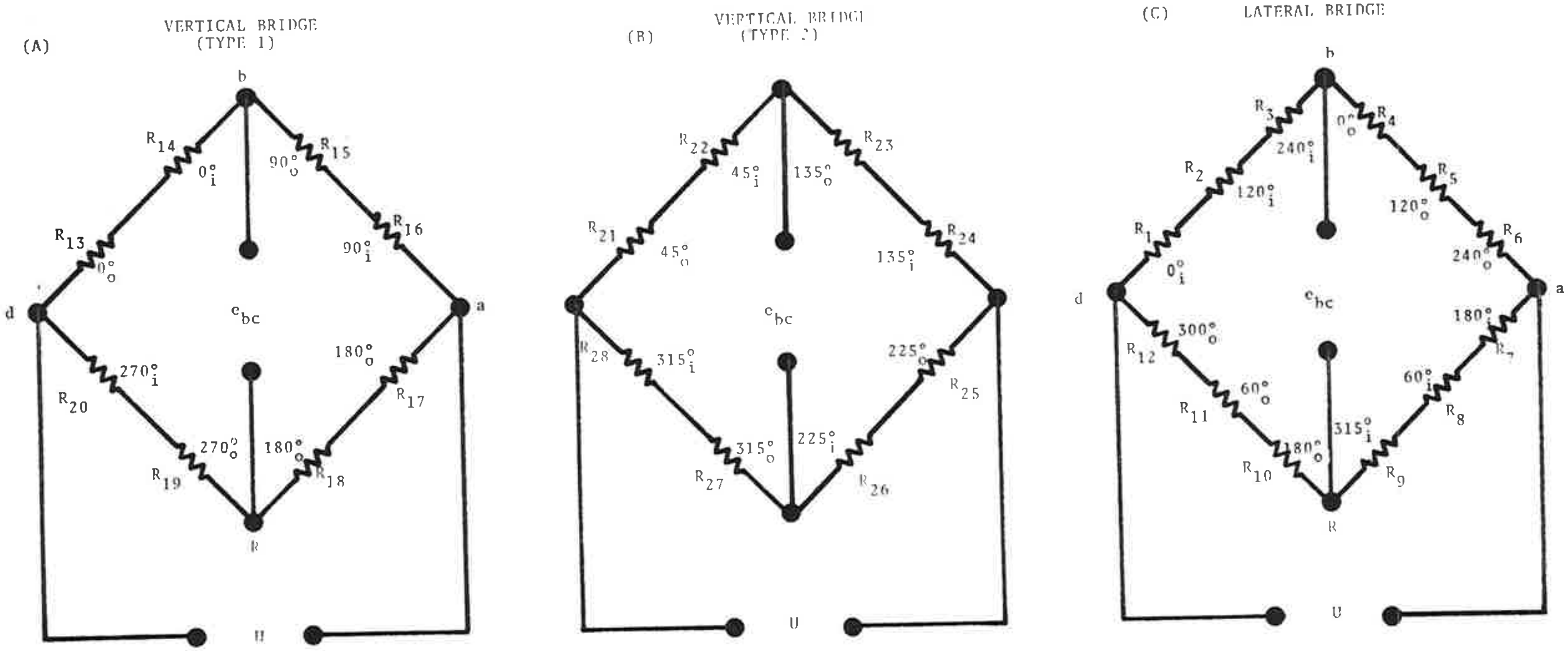


FIGURE 10. CIRCUIT DIAGRAMS OF THE STRAIN GAUGE BRIDGES USED IN THE PLATE INSTRUMENTED WHEELS: (A) & (B) TWO HALF BRIDGES FOR MEASUREMENT OF BENDING STRAINS ONLY: (C) FULL BRIDGE FOR MEASUREMENT OF BENDING STRAINS ONLY

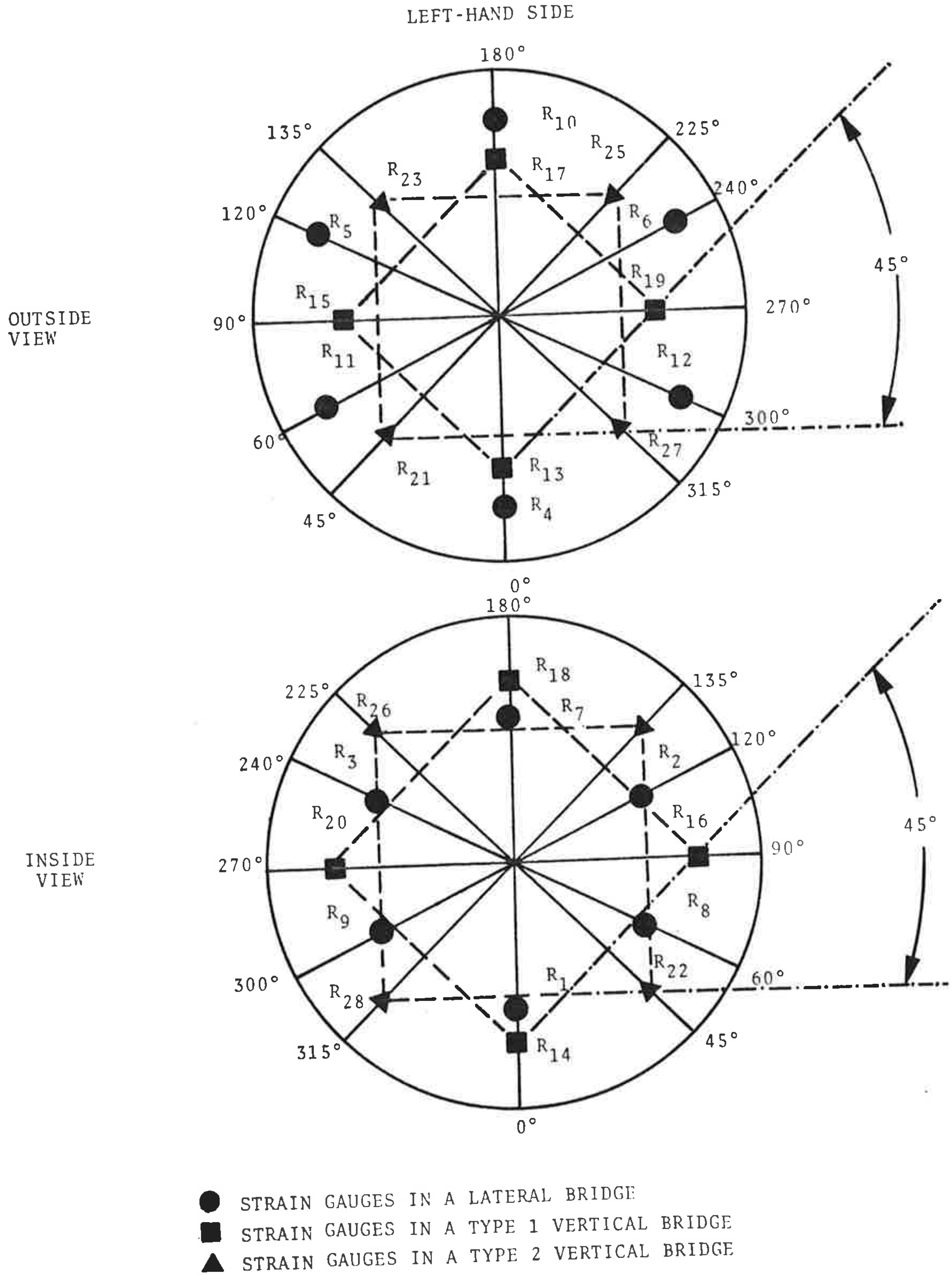
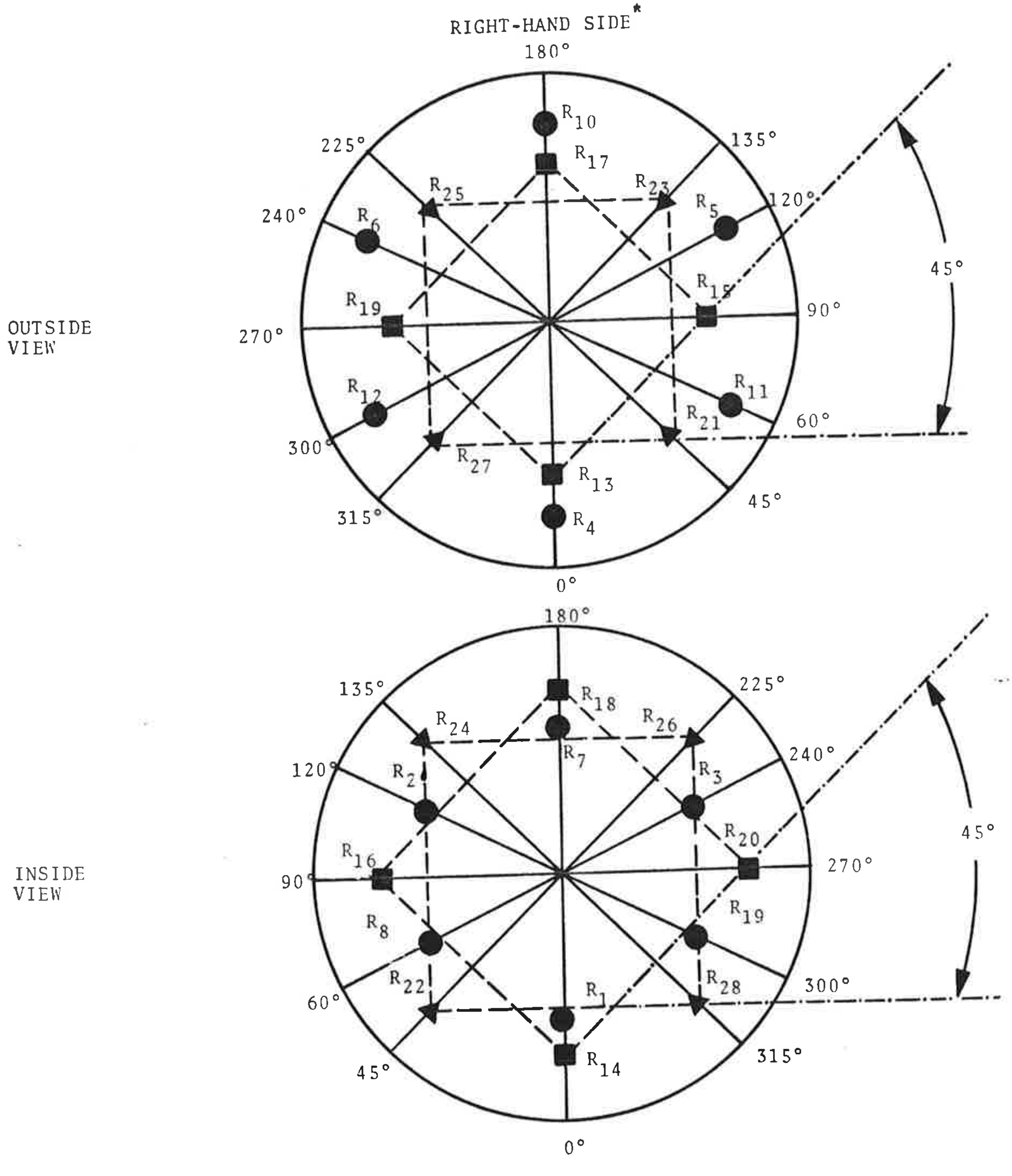


FIGURE 11A. DIAGRAM INDICATING THE POSITIONS OF STRAIN GAUGES ON THE INSTRUMENTED PLATE WHEELSETS: LEFT-HAND SIDE



* BULL GEAR SIDE

● STRAIN GAUGES IN A LATERAL BRIDGE

■ STRAIN GAUGES IN A TYPE 1 VERTICAL BRIDGE

▲ STRAIN GAUGES IN A TYPE 2 VERTICAL BRIDGE

FIGURE 11B. DIAGRAM INDICATING THE POSITIONS OF STRAIN GAUGES ON THE INSTRUMENTED PLATE WHEELSETS: RIGHT-HAND SIDE

signal is more nearly accomplished for the lateral bridges by distributing the gauges symmetrically around the wheel. This is the technique pioneered by Olson and Johnsson (1960). The interent variations are low enough (3-5%) that no futther processing of the data is required.

4. SYSTEM DESCRIPTION

4.1 OVERVIEW

A wheel/rail force measurement system is diagrammed in Figure 12. The symbol used to represent the force transducer is that approved in ISA (1976). The forces on the wheel are coverted into electrical resistance changes in the various legs of the strain gauge bridges which in turn gives rise to voltage changes at the bridge outputs. These voltage signals are fed along various cable runs through a slip ring assembly to the wheel signal processor. The wheel signal processor converts the signals from the vertical bridges into a continuous signal using information from the lateral strain gage bridge to enter a slight correction into the analog algorithm. The strain gages are driven by an AC voltage. The voltage changes resulting from strains are taken from the carrier signal by a phase sensitive demodulator as illustrated in Figure 13.

Each of the individual components will be described in enough detail to provide the necessary information to understand the basic functions of each.

4.2 WHEELSETS

Each wheelset consists of two wheels and an axle with a bull gear as shown in Figure 14. The wheels are 40-in. (1016-mm) in diameter having an S-shaped plate region (see Figure 15) with a conical taper (1:40) tread. The wheels and axles were manufactured by the Surahammar Works in Surahammar, Sweden. There were several small (0.25-in. [6.35-mm]) diameter holes drilled through the plate region to allow for wiring of the strain gauge bridges.

ISA, (1976), Standard specifications and tests for strain gauge force transducers, Standard No. ANSI/ISA-S37-.8, Instrument Society of America, Pittsburgh PA.

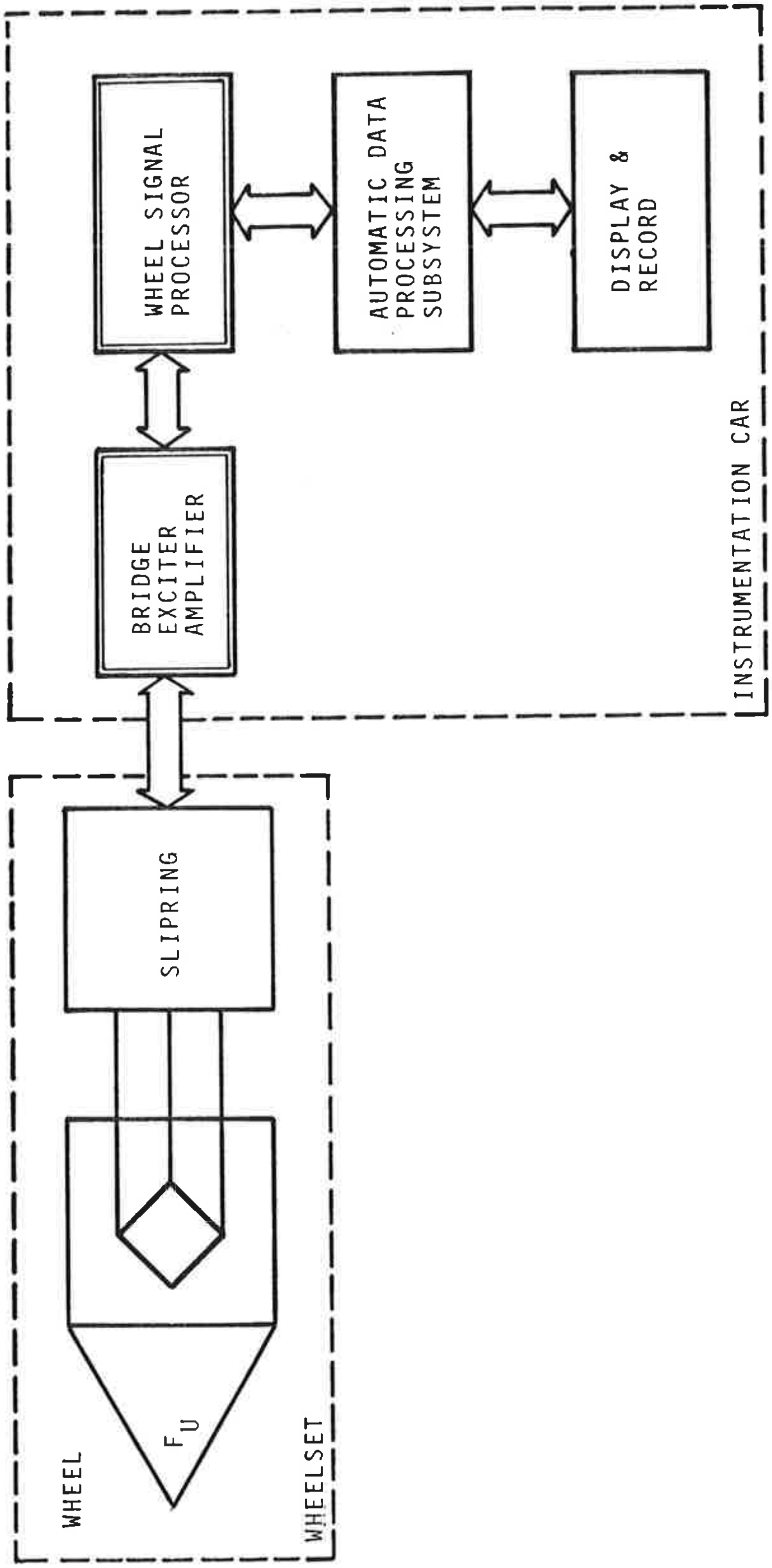


FIGURE 12. FUNCTIONAL BLOCK DIAGRAM OF THE WHEEL/RAIL FORCE MEASUREMENT SYSTEM

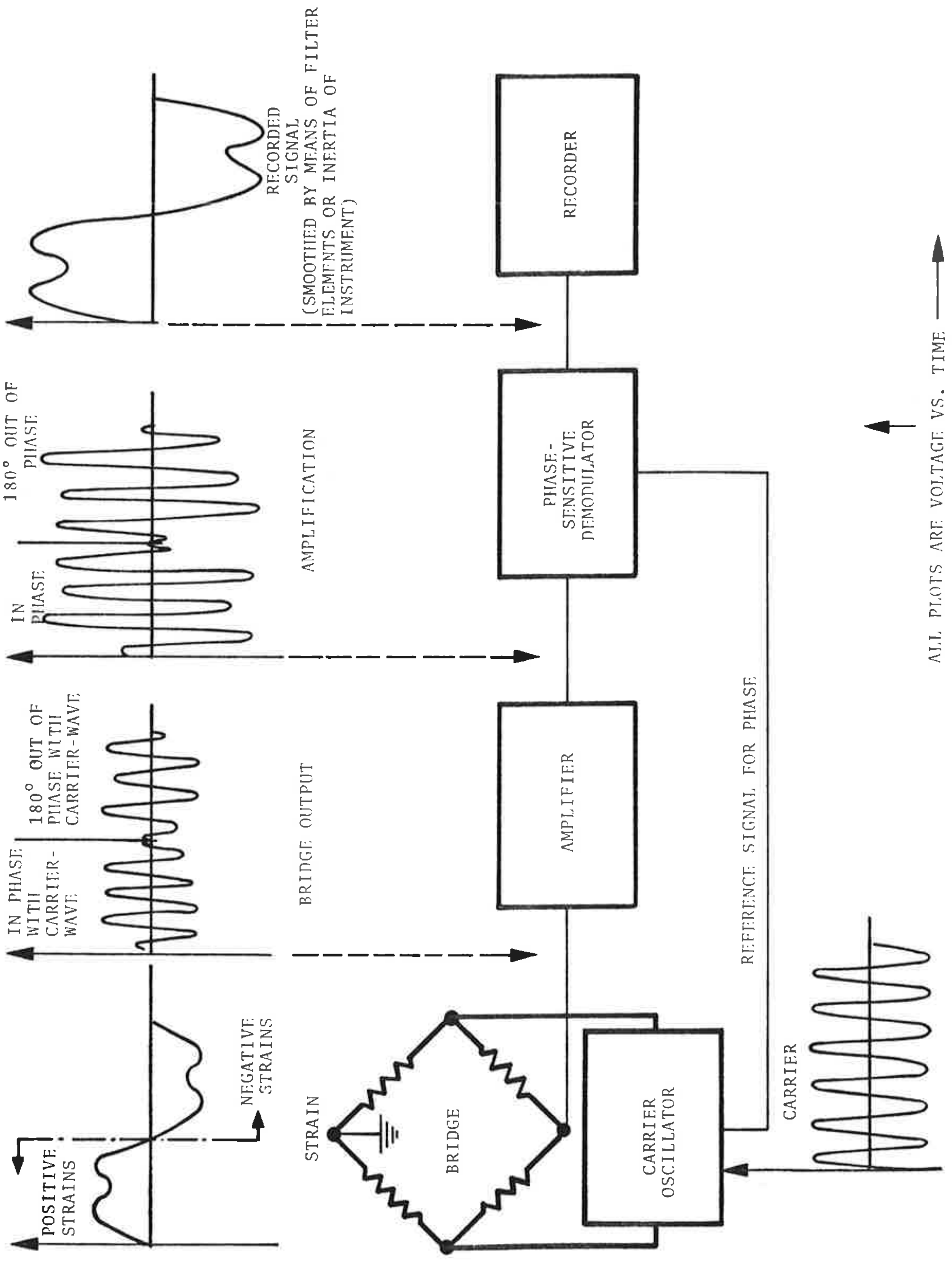


FIGURE 13. SIGNAL FLOW DIAGRAM OF A STRAIN GAUGE BRIDGE WITH AC CARRIER

NOTE : TO be supplied

FIGURE 14. PHOTOGRAPH OF PARTIALLY ASSEMBLED ASEA/SJ INSTRUMENTED WHEELSET (JUNE 1978)

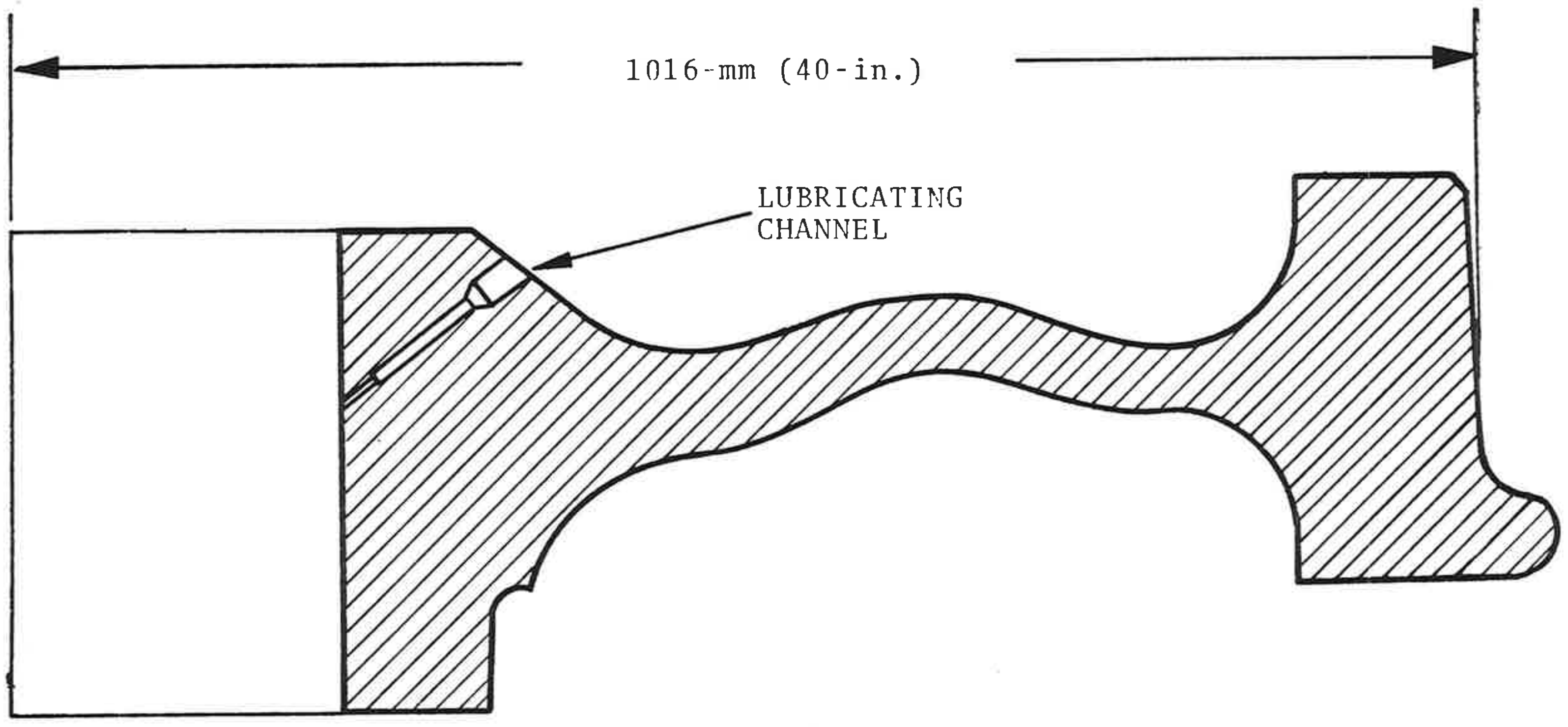


FIGURE 15. MODIFIED DIAGRAM OF THE S-SHAPED WHEEL USED ON THE INSTRUMENTED WHEELSET (AFTER SURAHAMMAR DRAWING NO. 3.1749.2)

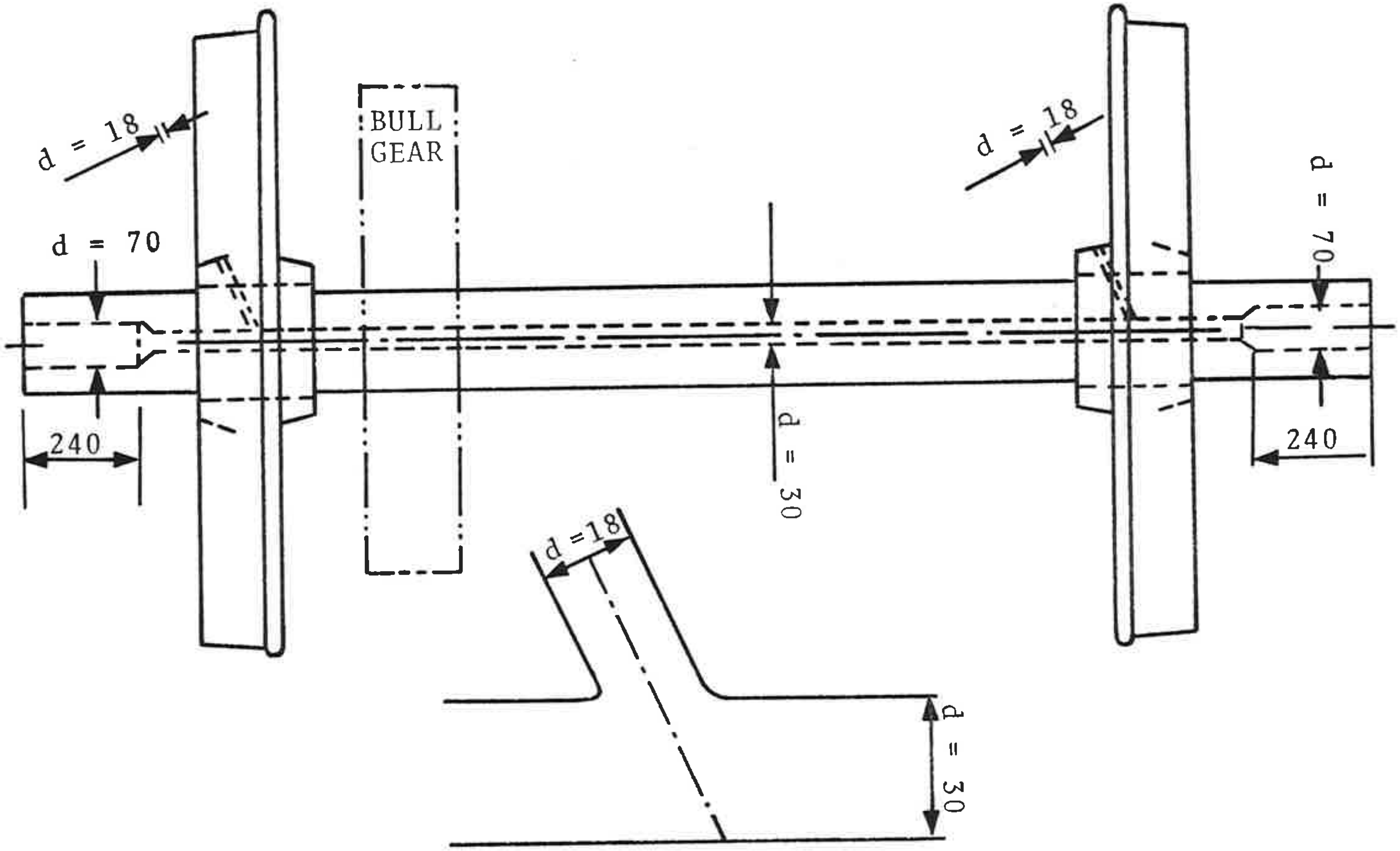
The wheels were shrink fitted onto all-turned axles. During the process the wheels were slowly heated to 210-240°C, which is well below the tempering temperature of 450°C. In the center of the axle there is a 1.18-in. (30-mm) diameter hole bored through the entire length. At one end there is a 2.76-in. (70-mm) diameter hole drilled 9.45-in. (240-mm) long into the axle center to house the slip ring assembly. Figure 16 illustrates the axle and bull gear.

4.3 STRAIN GAUGE BRIDGE WIRING

The strain transducers used in the instrumented wheelset subsystem are commercially available, temperature compensated, constant wire type strain gauges. The temperature coefficient of the resistance wire is matched to steel with a thermal expansion coefficient (α) of $12.0 \times 10^{-6}/°C$. The gauges have an ohmic resistance of 120 ohms, which are generally accepted for good self-heating properties (Holister, 1967, p. 94). The dimensions of the active area are 0.078-in. (2-mm) wide and 0.256-in. (6.5-mm) long.

The circuit diagrams of the strain gauge bridges used in making lateral force measurements were given in part A of Figure 10. Because there are three strain gauges per arm the total resistance of bridge is 360 ohms. The circuit diagrams of the strain gauge bridges used in making vertical force measurements were shown in parts B and C of Figure 10. Because there are two strain gauges per arm the total resistance of the bridges is 240 ohms.

Shielded, single wire cables are used to connect the strain gauges on the wheel plate. Because of the rotating strain gauge system, it is necessary to transfer the electrical signals to a nonrotating system. One effective way is by the use of a commercially available slip ring device in which both the Wheatstone bridge supply voltages and the resulting strain voltages are transferred through brushes in contact with rotating annular surfaces. The cables are wired into bridges at connection boards



NOTE: ALL DIMENSIONS IN mm.

FIGURE 16. DIAGRAM OF WHEELSET SHOWING THE SPECIAL HOLES BORED FOR THE PASSAGE OF THE STRAIN GAUGE CIRCUIT WIRING

located on the plate region of the wheels. Between the connection boards and the slip ring device, 4-wire shielded cables are used giving a total of six such cables at each slip ring device so that it must have 24 leads and an electrical ground.

4.4 CABLING

The cabling between the slip ring device on the axle and the bridge exciter/amplifier is shielded and durable to resist the severe railroad environment.

4.5 STRAIN GAGE BRIDGE EXCITER/AMPLIFIER

The bridge exciter/amplifier is a commercially available AC carrier amplifier with a carrier frequency of 6 kHz. The basic principle of operation was shown in Figure 13.

4.6 WHEEL SIGNAL PROCESSOR

The wheel signal processor (known as the Q-shaper in Swedish nomenclature) is a custom built electronic instrument which converts individual signals from the vertical strain gauge bridges mounted on the wheelsets into continuous analog output signals. To accomplish this, two separate bridges for measuring vertical forces are mounted on each wheel at an angle of 45° from each other. For example, the Wheatstone bridges made up of vertical bridges type 1 and type 2 in Figure 10 are mounted at an angle of 45° as was indicated in Figures 11-A and 11-B. Each Wheatstone bridge is connected in such a way as to give a signal that is approximately a sine wave with a frequency of two cycles per revolution, as shown in Figure 17.

The wheel signal processor first amplifies the signal U_1 and U_2 from the signal bridges to a suitable signal level and rectifies both signals, giving the absolute value $|U_1|$ and $|U_2|$, respectively. These two signals are then summed to give a third combined signal U_3. The amplitude of U_3 is adjusted to give the same amplitude as the maximum of U_1 or U_2.

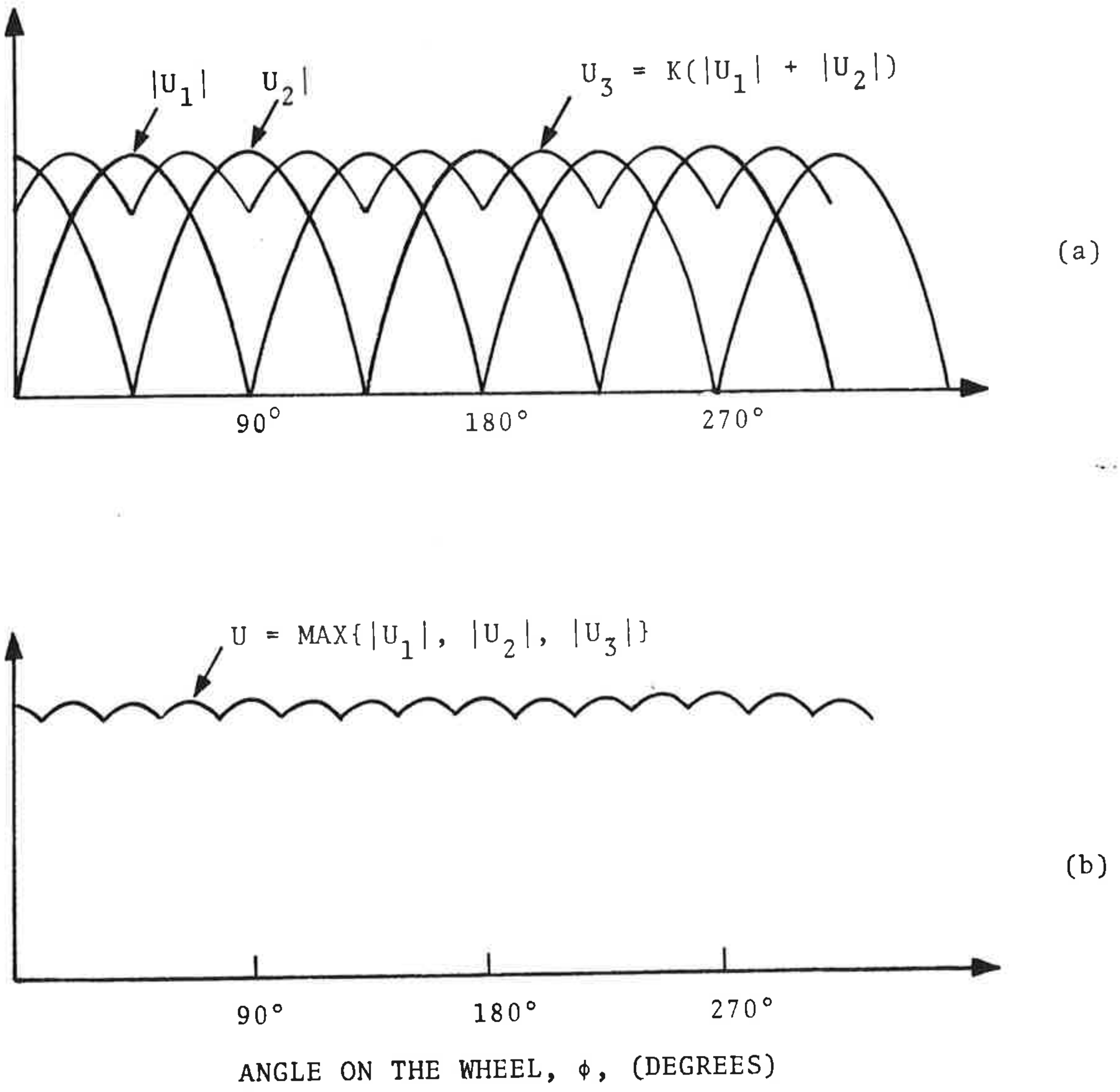


FIGURE 17. ANGULAR DIAGRAM OF SIGNALS FROM THE TWO VERTICAL (V) STRAIN GAUGE BRIDGES ON EACH WHEEL OF THE ASEA/SJ INSTRUMENTED WHEELSETS WITH A CONSTANT VERTICAL FORCE

The signal U_1, U_2, or U_3 which has the largest amplitude at any given time is treated as the true vertical signal. This resulting signal (U) is continuous in nature and has approximately 5% ripple. The signal is then filtered in the wheel signal processor.

As the vertical signals are sensitive to even the lateral, forces a slight compensation is made for each vertical signal.

4.7 CALIBRATION

The characteristics of wheelsets would be incomplete without discussing the calibration procedures. Each of the wheels was calibrated in a dynamic test fixture and the resulting data recorded on stripcharts. A field calibration is performed to check the condition of the wheels after shipping. The results of combining field and laboratory calibration values on the three wheelsets (six wheels) described herein is summarized in Table 1. Note that the vertical and lateral sensitivities vary by a factor of approximately three indicating that the wheel bends more readily laterally than it does in vertical compression.

The lateral-to-vertical crosstalk can be eliminated by proper signal processing. Thus, although further developments could be undertaken to determine the two unknown parameters, they are considered to be second-order effects and the wheelsets are in fact accurate force transducers within the stated limits of error.

TABLE 1. SUMMARY OF THE CALIBRATION VALUES OF THE SIX 40-in. (1016-mm) DIAMETER INSTRUMENTED LOCOMOTIVE

PARAMETER	VALUE
Mean vertical sensitivity (μin/in/kip)	4.13
Mean lateral sensitivity (μin/in/kip)	15.41
Vertical-lateral crosstalk	negligible
Lateral-vertical crosstalk (%)	0-13
Lateral and vertical sensitivity to position of vertical reaction	negligible
Lateral and vertical sensitivity to position of lateral reaction	unknown
Lateral and vertical sensitivity to centrifugal loading	negligible
Lateral and vertical sensitivity to wheelplate temperature variations	unknown
Average lateral ripple (%)	±2.1
Average vertical ripple from wheel signal processor output (%)	±5.8

5. SYSTEM CALIBRATION

5.1 ANALYTICAL TRANSDUCER/WHEEL PROPERTIES

All wheel plates on the three instrumented wheelsets have the same arrangement of strain gauges described below. However, each strain gauge is individually placed and tested for final placement. On each wheel there are three Wheatstone bridges: one is for measuring the lateral force and the other two are for measuring the vertical force.

5.2 STRESS/STRAIN RELATIONSHIP

The stress/strain relationship on the wheels was preliminaryly determined by using an ASEA developed finite element analysis of the S-shaped and conical shaped wheel plates.

ASEA has a proprietary wheel analysis computer program which uses the following parameters as input: vertical, lateral, and centrifugal forces, moment and over-temperature. Basically, the wheel analysis program uses finite element and Fourier analysis techniques to compute the radial distribution of various load parameters. The results are manipulated to optimize the output from vertical and lateral loads to eliminate the crosstalk. A typical result was presented in Figure 11.

Proprietary computer programs for conical wheels have been developed in the United States. However, a new program which has become publically available (Johnson and Yeung, 1978) has recently been developed. Some results based on that program were shown in Figure 8.

Results of the preliminary laboratory testing of the ASEA/SJ instrumented wheelsets were provided in Table 1.

6. POSTLUDE

This report has provided background, expounded the principle of operation of instrumented wheelsets, and presented a specific example of the application of the principles to three specific locomotive wheelsets. Table 2 contains a summary of the characteristics for the example presented.

The wheelsets discussed herein were used in a series of field tests co-sponsored by the AAR, Amtrak and the FRA in the fall of 1978. These Perturbed Track Tests were successfully completed in December 1978. Data obtained with the wheelsets will be included in reports being prepared on these tests.

TABLE 2. SUMMARY OF CHARACTERISTICS OF THE 40-IN. (1016-mm) DIAMETER INSTRUMENTED LOCOMOTIVE WHEELSETS

Feature	Value	
	Vertical Force Bridges	Lateral Force Bridges
Type of strain gauges*	wire	wire
Number of bridges per wheel	2	1
Orientation of bridges	45°	-
Number of Strain gauges per bridge arm	2	3
Strain gauge locations	Fig. 3-7A, B	Fig. 3-7C
Signal processing	wheel signal processor	-
Typical bridge sensitivity (μV/kip)	12	36

*The strain gauges in one wheel of each of two wheelsets of the three manufactured in this lot were accidentally damaged and the strain gauges were replaced with foil type gauges of similar characteristics.

7. BIBLIOGRAPHY

Anon. (1974), Instrumentation for measurement of forces on wheels of rail vehicles, Rpt. No. FRA-ORD&D-75-11, Association of American Railroads, Chicago IL and ENSCO, Inc., Springfield VA.

Burada, C., M. Buga, L. Nailescu and A. Popistas, (1978), Possibilities to improve sensitivity of the methods for the Q-force measuring by means of spoke wheels and disk wheels, pp. 3-4-1 through 3-4-18 in the Proceedings of Sixth International Wheelset Congress, Colorado Springs CO, October.

Dolecki, E. A. and C. E. Hartzell, (1974), Operating and ride qualities, three axle, floating bolster truck, GE Technical Information Series DF74LC2690, General Electric Co., Erie PA.

ENSCO, (1977), SDP-40F/E-8 locomotives - test results report: Dynamic performance testing, Rpt. No. DOT-78-10, Vol. II, ENSCO Inc., Engineering Test & Analysis Div., Alexandria VA.

Eriksson, S. and A. Nellgran, (1978) Improved signal conditioning methods for measuring the vertical forces at the wheel/rail interface, Rad/Schiene, ZEV-Glas. 102, (5), 143-146, (In German).

Hearn, E. J. (1971), Strain Gauges, Merrow Publ. Co., Ltd., Watford, England.

Holister, G. S., (1967), Experimental Stress Analysis: Principles and Methods, Cambridge Univ. Press, Cambridge, England.

ISA, (1976), Standard specifications and tests for strain gauge force transducers, Standard No. ANSI/ISA-S37-.8, Instrument Society of America, Pittsburgh PA.

Johnson, M. R. and K. S. Yeung, (1978), Application of finite element analysis to the study of railroad wheel failure phenomena, pp. 387-403 in Track/Train Dynamics & Design: Advanced Techniques, Edited by G. J. Moyar, W. D. Pilkey and B. F. Pilkey, Pergamon Press, New York.

BIBLIOGRAPHY (CONTINUED)

Koci, L. F. and H. A. Marta, (1965), Lateral loading between locomotive truck wheels and rail due to curve negotiation, ASME Paper No. 65-WA/RR-4, also in Anthology of Rail Vehicle Dynamics, Vol. III, Axles, Wheels and Rail-Wheel Interactions, S. G. Guins and C. E. Tack, kditors, American Society of Mechanical Engineers, New York, pp. 119-129

Kunieda, M. (1970), Theoretical study on the side thrust of truck wheels running on curves, Q. Rpt. Railway Tech. Res. Inst., 11, (2), 105-108.

Modransky, J., W. J. Donnelly, S. P. Novak and K. R. Smith, (1979), Instrumented locomotive wheels for continuous measurements of vertical and lateral loads, ASME Paper No. 79-RT-8, American Society of Mechanical Engineers, New York.

Olson, P. E. and S. Johnsson, (1959), Lateral forces between wheel and rail, Glas. Ann., 83, (5), 153-161. (In German).

Olson, P. E. and S. Johnsson, (1960), Lateral forces between wheels and rails - an experimental investigation, ASME Paper No. 60-RR-6, American Society of Mechanical Engineers, New York, also in Axles, Wheels and Rail-Wheel Interaction, Vol. III of the Anthology of Rail Vehicle Dynamics, ASME, New York, pp. 253-262, (1973).

Prause, R. H. and H. D. Harrison, (1975), Data analysis and instrumentation requirements for evaluating rail joints and rail fasteners in urban track, Rpt. No. DOT-TSC-UMTA-75-2, Battelle Columbus Laboratories, Columbus OH.

Shafranovskii, A. K. (1965), Continuous Recording of Vertical and Lateral Forces of Interaction Between a Wheel and a Rail, TsNIP MPS (Central Scientific Research Institute, Ministry of Rolling Stock), USSR, (In Russian).

Wickens, A. H. and A. O. Gilchrist, (1977), Vehicle dynamics - a practical theory, Railway Engineer, 2, (4), 26-34.

APPENDIX

A DIMENSIONLESS WHEEL/RAIL DYNAMICS PARAMETER

A.1 BACKGROUND

In rail vehicle dynamic analyses the lateral wheel/rail force and the vertical wheel/rail force are of primary interest because these forces are indicators of the potential problem of flange climbing, which can occur when a laterally-loaded wheel flange rolls forward while being pressed against the rail. Under certain conditions the flange can support the equilibrium of the wheel in question; then any increase in lateral force will cause it to climb up the side of the rail, or possibly rail rollover may occur. This equilibrium condition of "incipient" flange climbing has been sought in many analyses and the ratio of the lateral wheel/rail force to the vertical wheel/rail force has been used by many administrations as a measure of the degree of danger due to possible derailment. Table A-1 lists 15 such ratios indicating the same dimensionless wheel/rail dynamics parameter. Analysis of the table shows that:

a) Q represents the vertical wheel/rail force in European (ORE) notation and the lateral wheel/rail force in Japanese notation.

b) The letter L lacks universality as a symbol for the lateral wheel/rail force as it is the symbol for the lambert which is the unit of luminance in the Centimeter Gram Second (CGS) System of Units.*

C) The letter V lacks universality as a symbol for the vertical wheel/rail force as it is the symbol for the volt which is the unit of electromotive force in the International System of Units (SI). (Anon. 1975),

---

*The International System (SI) unit, candela per square meter is preferred. (Anon. 1975, pp. 3-4).

Anon. (1975), Units, constants and conversion factors, Ch. 3 in Reference Data for Radio Engineers, Howard W. Sams & Co., New York.

TABLE A-1. TERMS USED TO DESCRIBE A DIMENSIONLESS WHEEL/RAIL DYNAMICS VARIABLE

No.	Term	Symbol*	Reference(s)
1	coefficient of derailment	Q/P	Nakamura and Tanaka (1967)
2	coefficient of the safety against derailment	Y/Q	ORE (1970)
3	derailment coefficient	Y/Q	Yokose (1966) Tanahashi (1973)
4	derailment ratio	Y/Q	Gilchrist and Brickle (1976)
5	derailment criterion	$(Y/Q)_{lim}$	ORE (1970)
6	derailment quotient	Q/P Q/P Y/Q Y/Q L/V	Matsui (1955) Yokose (1966) ORE, (1970) Gilchrist and Brickle (1976) Jeffcoat (1977)
7	derailment related performance index	L/V	Dimasi and Weinstock (1978)
8	lateral-to-vertical ratio	L/V	Anon. (1974)
9	lateral-to-vertical force ratios	L/V	Anon. (1974)
10	L/V performance index	L/V	Dimasi and Weinstock (1978)
11	L/V ratio	L/V L/V	Anon. (1977) Dimasi and Weinstock (1978)
12	ratio of lateral to vertical forces	L/V	Cooperrider and Law (1978)
13	ratios of lateral to vertical (L/V) wheel loading	L/V	Anon. (1977)
14	ratio Y/Q	Y/Q	Gilchrist and Brickle (1976)
15	Y/Q ratios	Y/Q	Gilchrist and Brickle (1976)

*See Section A-2 for the definition of the nomenclature.

d) The letter P lacks universality as a symbol for the vertical wheel/rail force as it is the symbol for the prefix peta which is a multiple of 10^{15} in the metric system, and

e) The use of such terms as "L/V ratio," "ratio Y/Q," etc., is redundant and awkward.

For these reasons it is proposed to define an unambigious quantity and symbol for adoption as a universal standard for the measurement of derailment tendency in Section A.3.

A.2 NOMENCLATURE

CGS	Centimeter Gram Second System of Units
F_ℓ	lateral wheel/rail force
F_t	tangential wheel/rail force
F_v	vertical wheel/rail force
lim	limit
L	lateral wheel/rail force (American usage)
ORE	Office for Research & Experiments of the International Railway Union
P	vertical wheel/rail force (Japanese usage)
Q	vertical wheel/rail force (European usage, ORE) <u>or</u> lateral wheel/rail force (Japanese usage)
SI	International System of Units
V	vertical wheel/rail force (American usage)
Y	lateral wheel/rail force (European usage, ORE)
δ	index of derailment

A.3 PROPOSED PARAMETER

Before presenting the proposed dimensionless wheel/rail dynamics parameter, it seems appropriate to discuss the symbology of the component parts. The wheel/rail forces should be indicated by the symbol "F" because F is the symbol traditionally used in the fundamental definition of force. (Baumeister et al. 1975, p.

3-3). Therefore, it is proposed that the following symbols be considered for use in describing wheel/rail forces:

F_ℓ = lateral force at the wheel/rail interface (A-1)

F_t = tangential force at the wheel/rail interface (A-2)

F_v = vertical force at the wheel/rail interface (A-3)

where the directions are shown in Figure A-1.

The parameter proposed to unify the various symbols will be called the "index of derailment" since this term has not been used in any of the literature examined to date and is fully descriptive of the meaning of the dimensionless parameter it represents. The defining equation is:

$$\delta \equiv \text{index of derailment} \equiv F_\ell/F_v \tag{A-4}$$

The Greek letter δ was chosen since it transliterates to the Roman d which could be a useful mnemonic to indicate derailment. Secondly, it is not used in any system of units and thirdly, the most closely related Roman letters would have been ID, which usually stands for inside diameter or identification (Baumeister et al. 1975).

Baumeister, T., E. A. Avallone and T. Baumeister, III, (1978), Marks' Standard Handbook for Mechanical Engineers, 8th Edition, McGraw-Hill, New York.

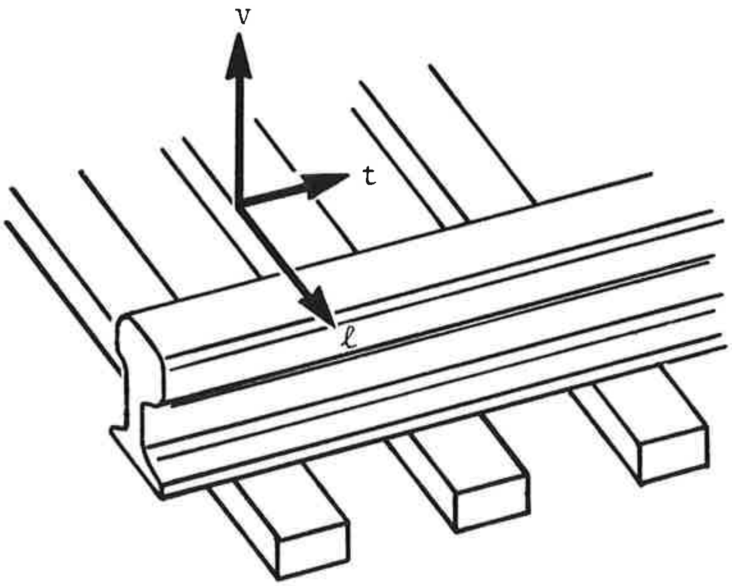


FIGURE A-1. DIAGRAM INDICATING THE ORIENTATION OF THE LATERAL (ℓ), VERTICAL (v), AND TANGENTIAL (t) DIRECTIONS ON A TRACK SYSTEM

A.4 BIBLIOGRAPHY

Anon. (1974), Instrumentation for measurement of forces on wheels of rail vehicles, Rpt. No. FRA-ORD&D-75-11, AAR, Chicago IL and ENSCO, Inc., Springfield VA, (PB-247154).

Anon. (1975), Units, constants and conversion factors, Ch. 3 in Reference Data for Radio Engineers, Howard W. Sams, Inc., New York.

Anon. (1977), Derailment study report, Vol. I - Analyses, Vol. II - Appendices, Rpts. on MBTA Contr. by Kaiser Engineers, Inc., Oakland CA.

Baumeister, T., E.A. Avallone and T. Baumeister, III, (1978), Marks' Standard Handbook for Mechanical Engineers, 8th Edition, McGraw-Hill, New York.

Cooperrider, N.K. and E.H. Law, (1978), A survey of rail vehicle testing for validation of theoretical dynamic analyses, Trans. ASME, J. of Dynamic Systems, Measurement, and Control, 100, 238-251.

Dimasi, F. and H. Weinstock, (1978), A parametric study to relate railcar speed to permissible combinations of track geometry deviations, Trans. ASME, J. Dynamic Systems, Measurement, and Control, 100, 252-259.

Gilchrist, A.O. and B.V. Brickle, (1976), A re-examination of the proneness to derailment of a railway wheel-set, J. Mech. Eng., 18, (3), 131-141.

Jeffcoat, R.L. (1977), Statistics of the ratio of two gaussian random process-exact and approximate exceedance of the L/V ratio, as cited in Demasi and Weinstock (1978).

Matsui, N. (1966), On the derailment quotient Q/P, Railway Technical Research Inst., Quart. Rpt. as cited in Gilchrist and Brickle (1976).

Nakamura, H. and S. Tanaka, (1967), Lateral forces acting to wheel, wheel load, coefficient of derailment and bending stress of wheel-axle of the car on the new Tokaido truck line, Railway Technical Research Inst., Quart. Rpt., 8, (2), 103-106.

ORE, (1970), Prevention of derailment of goods wagons on distorted tracks, Doc. No. B 55/RP 4/E, Rpt. No. 4, Office for Research and Experiments, International Union of Railways, Utrecht, The Metherlands.

Tanahashi, H. (1973), Derailment coefficient and climbing probability of wheel flange, Railway Technical Research Inst., Quart. Rpt., 14, (1), 29-34.

Yokose, K. (1966), A theory of the derailment of wheel set, Railway Technical Research Inst., Quart. Rpt., 7, (3), 30-34.