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# FABRICATION AND EVALUATION OF A RESONANT NON-DESTRUCTIVE TIRE-TESTING SYSTEM

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PRELIMINARY MEMORANDUM



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16. Abstract

A method of detecting faults in tires by means of vibration measurements was investigated. A tire-roll-tester rig was modified to accommodate a vibrator and a detector to measure the response across the tire.

Different kinds of faults could be identified under various experimental conditions. But it was not found possible, up to the point where the present tests had to be abandoned, to distinguish the faults from other disturbances in the tire. Shortage of funds prevented some simple corrective tests to be carried out.

The modes of vibration of a tire were defined and a method of visualization of the nodal patterns was devised.

17. Key Words
res, Non-destructive testing
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PREFACE

Resonance techniques for non-destructive testing of tires described in the report were used by the Massachusetts Institute of Technology, Department of Mechanical Transportation. This work was performed as a part of the Non-destructive Automobile Tire-testing Program sponsored by the Department of Transportation through the National Highway Traffic Safety Administration, Research Institute.

The object of this report was to develop a method of detecting faults in tires by means of vibration measurements.

The work described was supported in part by the U.S. Department of Transportation, Transportation Systems Center, under contract TSC/TRE 0037.

After contract funds were exhausted, internal funds from the Department of Mechanical Engineering, M. I. T., were provided for purchase of equipment and materials. Samy A. Loebl continued work for three months without salary.

Collaboration and guidance from the Transportation Systems Center were given by Messrs. Stephen Bobo, Harry Ceccom, and A. L. Lavery.

Professor Stephen P. Loutrel jointly supervised this project and contributed many valuable suggestions.

The staff of the Engineering Projects Laboratory and workshop were both forebearing and always helpful.

Ms. Anna M. Piccolo arranged and typed this final report.

To all of these, the project supervisor expresses his grateful thanks.

David Gordon Wilson
Professor of Mechanical Engineering

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# CHAPTER I

## INTRODUCTION

Analysis of the 1970 vehicle safety checks has shown that tires were most frequently reported as the least safe of any vehicle components. After almost a century since the development of the pneumatic tire there exists no equipment to test wheel-mounted tires and to determine their conditions and soundness.

The need for such equipment is growing, not only for the protection of the vehicle traveller, but also for the use of manufacturers and retreaders to check their products. In this project, a tire-testing system, first tried in 1967, was further investigated. An experimental rig was built to test the hypothesis presented in the original work and to illustrate the behavior of a tire when subjected to vibration.

## Previous research

The groundwork for this project was laid out by James Weigl in his master's thesis at MIT (Ref. 3) His study was concerned with inspection stations for increased vehicle safety and as a particular case he analyzed the aspect of tire inspection. He found in general that machinery suitable for automatic inspection of the whole vehicle was only in its developmental stages, sparked by the boom in diagnostic centers, and the cost of these machines would be extremely high due to limited production. Even so, there were no methods available for checking the integrity of mounted tire casing. His aim therefore was to discover simple methods for testing tires while on the vehicle.

From a range of initial considerations he finally chose three methods as the most promising and proceeded to run tests on each of them to determine their feasibility. The first method, static measurement, was based on the presumed uniformities of the force necessary to deflect a sound tire a given distance around the tire. The stiffness should be erratic if faults were present. This procedure was eliminated as it became apparent that to test the tire in this manner while on the vehicle would require bulky apparatus, not suitable for the application.

The second method was a heat-buildup test. After the tire was rotated at high speed it was scanned using an infrared technique. Hot spots in the output indicated the boundaries of the weak areas that flexed more. The simple and inexpensive equipment used by Weigl was unable to identify hot spots sharply and positively and he abandoned this approach.

The third procedure investigated was a dynamic measurement. A tire was excited sinusoidally on one sidewall, and the response was measured across the tire. In this case the presence of faults in the casing seemed to distort the vibration patterns, which could be measured. Actual levels of transmission were not found to be important, while variations in this level as the input-output pair were displaced around the tire indicated the presence of a fault. Weigl found very promising first-cut results which were used as a basis for this project.

His conclusion that dynamic analysis was feasible, as mentioned above, sparked the need to continue research in this direction. A description of his apparatus as well as the modifications introduced here is presented later in the report.

## Advantages of vibration analysis

There is a four-fold justification to proceed with investigation of the vibration method as a feasible means for tire inspections. First, differing from most other methods, this could be an on-vehicle procedure, i.e. the tire would not have to be removed from the vehicle for the test; also, the apparatus needed could very adequately fit in the space around the tire under the car. Secondly, it could be a fast procedure, requiring just one or two revolutions for the tire past the input-output pair. Thirdly, the apparatus would be comparatively inexpensive, even when automated. Finally, a go-no-go decision could be made on a clear basis, since irregularities in the tire caused a major shift in the response across the tire in Weigl's experiments.

Furthermore, in the last few years dynamic analysis has come to be used extensively in other areas of nondestructive testing. The methods in use are either ultra-sound or vibration analysis, and have met acceptable results.

## CHAPTER II

## TESTING METHODS AND PROCEDURES

### Dynamic measurement

In the tests made by Weigl, transmittance levels were found to vary a great deal when faults were present in the tire; the data indicated that transmittance variation was close to twice the average value. Only tires with cuts or severed cords were tested, the apparatus being able to detect cuts 1/4-inch long or longer.

### Modes of vibration

An important part of the present research was devoted to understanding the manner in which a tire vibrates when excited sinusoidally. For this purpose the sidewalls were chosen as the surfaces of interest and throughout most of the experiments the input-output pair was placed on these surfaces. Vibrations of the tread were checked during the investigation of nodal patterns, and it appeared that information obtained from the sidewall response would be adequate.

Analytically, a sidewall can be partially represented by a flat anular disk. The principal modes of vibration of a full disk are shown in figure 1 (Ref. 1 ). One mode represents the vibration along a circumferential line; the nodal lines for this mode are formed along diameters of the tire and thus this mode is designated diametral (figure 2a). The circumferential mode has its nodal lines formed along circumferences (figures 2b).

Finally, in the tire there are also longitudinal modes of vibration along the cords; the vibration is parallel to the surface of the sidewall and is designated as the tangential mode (figure 2c).

The response across the tire, from the input vibrator to the output detector, is transmitted by a combination of these three modes. These are excited simultaneously and the isolation of their respective effects could not be carried out in this project.

Two testing methods were used to determine the nature of the transmission of vibration across the tire and to examine the influence

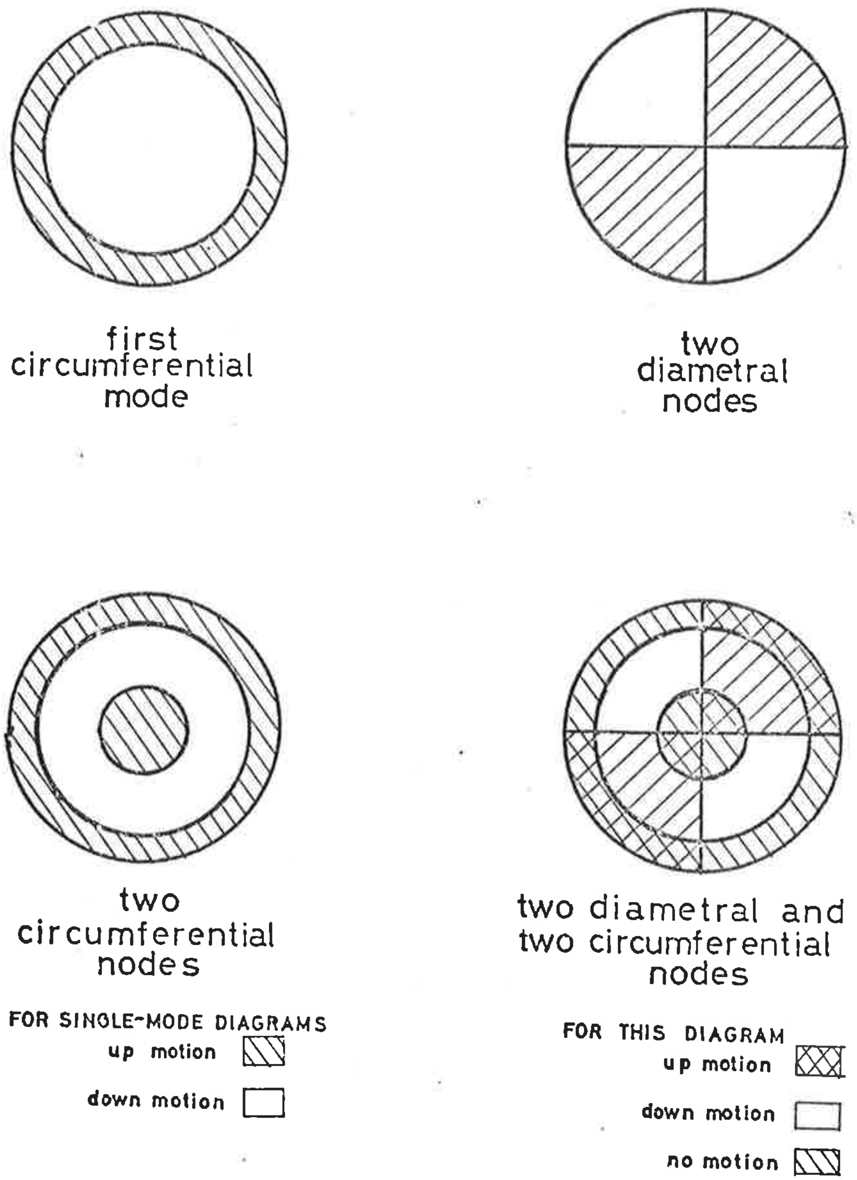
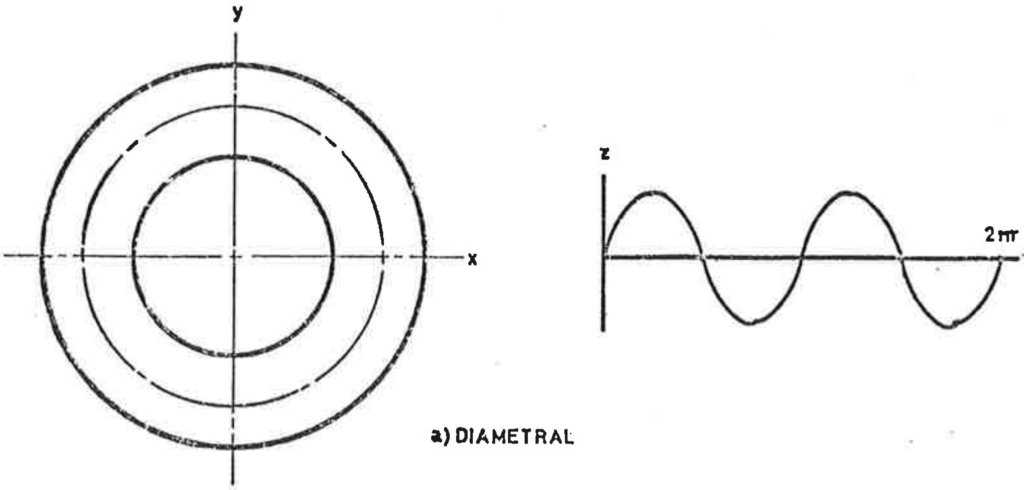
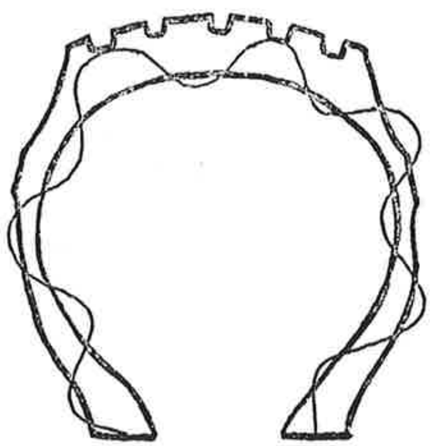



FIGURE 1. MODES OF VIBRATION OF A CIRCULAR PLATE




a) DIAMETRAL

b) CIRCUMFERENTIAL



c) TANGENTIAL

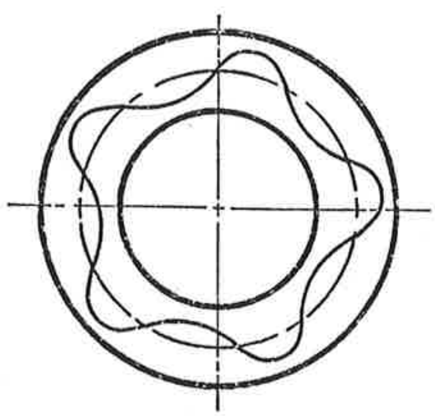


FIGURE 2. VIBRATION NODES AND DISPLACEMENTS OF A TIRE

of faults on the patterns of vibration. The first, response measurement, is similar to Weigl's dynamic measurement (Ref. 2 ). The second method, nodal-pattern inspection, is adopted from a method used in turbine-blade and turbine-disk analysis (Ref. 1 ).

## Response measurement

Response measurement consists in measuring the transmission of vibration across the tire using an input vibrator (shaker), an output detector and adequate signal-processing apparatus.

To proceed, the tire is mounted on the wheel at its normal pressure. This could be done in practice with the wheel attached to the vehicle. In the test rig, the wheel is on an axle and rotated by contact with a roller (figure 4). A vibration source is placed in contact with one sidewall while a vibration-sensitive detector (accelerometer) is in contact with the opposite sidewall. The frequency of vibration of the shaker is varied until a resonance peak (or natural-frequency response) is found through the accelerometer. Antinodes (points of maximum amplitude) for each natural frequency can be found by holding the shaker frequency constant and varying the relative positions of input and output on the circumference of the tire. The signal obtained from the accelerometer is filtered, amplified and rectified before observing and recording its magnitude (figure 3).

Typically, the first resonance peak was detected around 60 cps. This was taken to be the first-order standing wave travelling around the tire. Resonances occur at random intervals as frequency increases or as the relative position of the input-output pair is varied (figure 5). Most of the experiments were done around 250 cps where peaks were sharp and distinct in the passenger-car tires used.

Upon rotation of the tire, (with the positions of vibration input and output fixed in space), a variation in the response across the tire occurs as different sections of the tire, not exactly uniform in structure or composition, pass between the input-output pair. The range of variation for a new, sound tire can be contrasted to the variation that occurs when a major cut or fault is present.

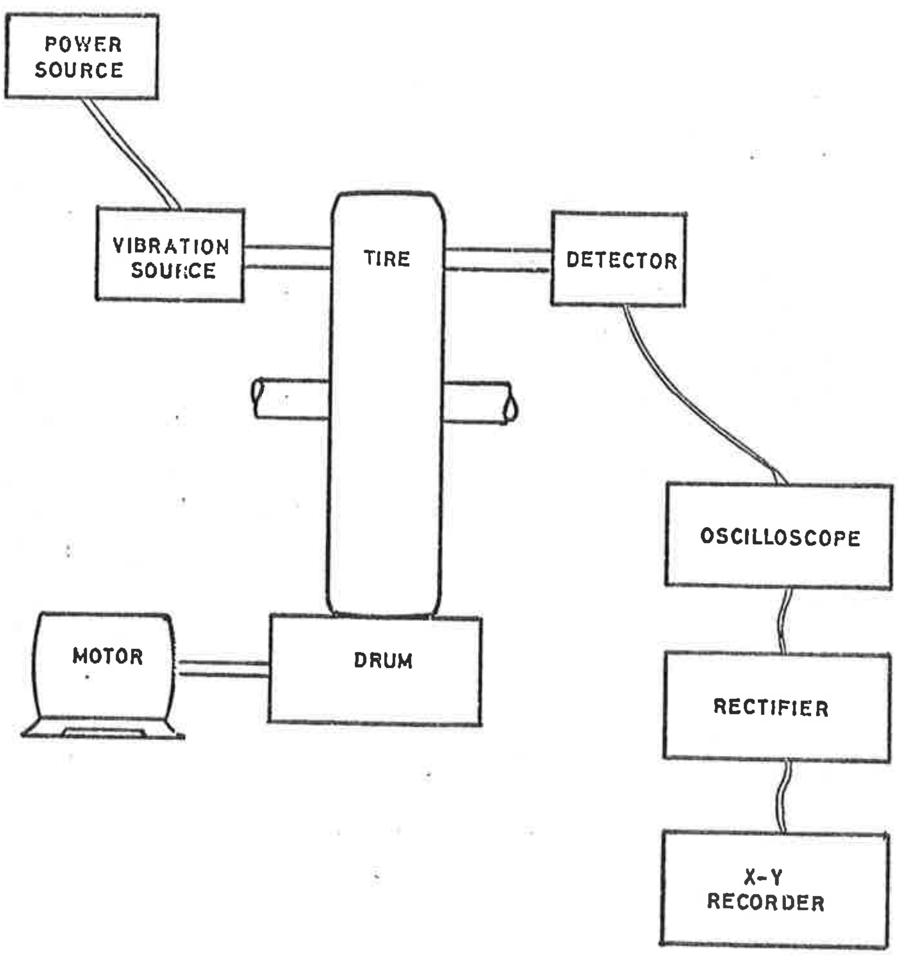



FIGURE 3. SCHEME FOR RESPONSE MEASUREMENT

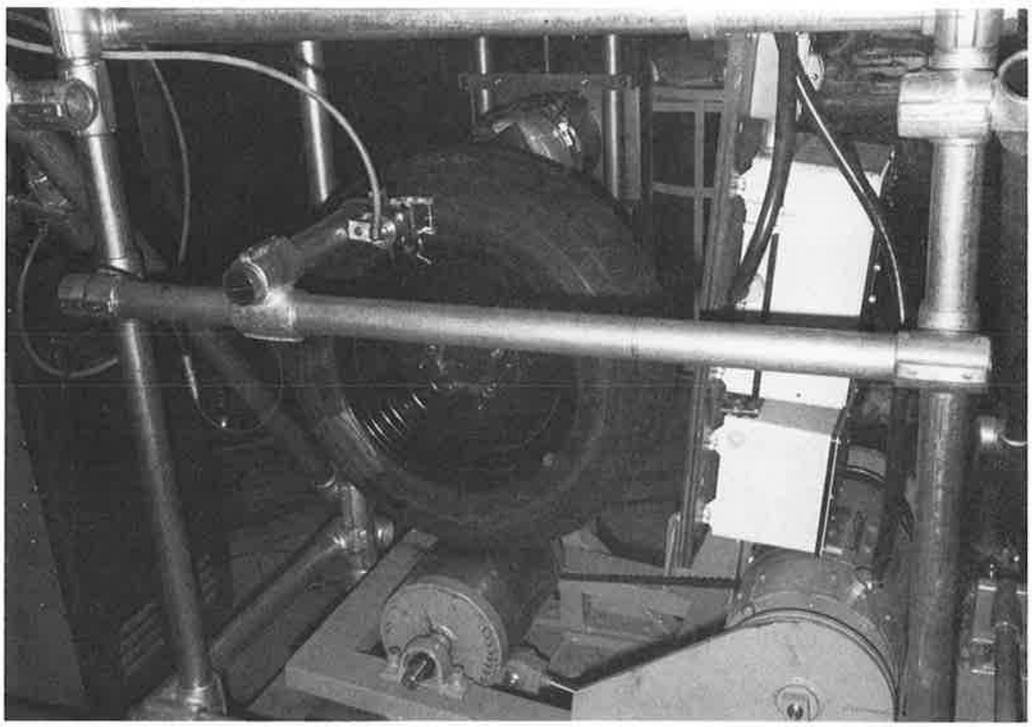


FIGURE 4. FRONT VIEW OF TIRE-ROLL TESTER

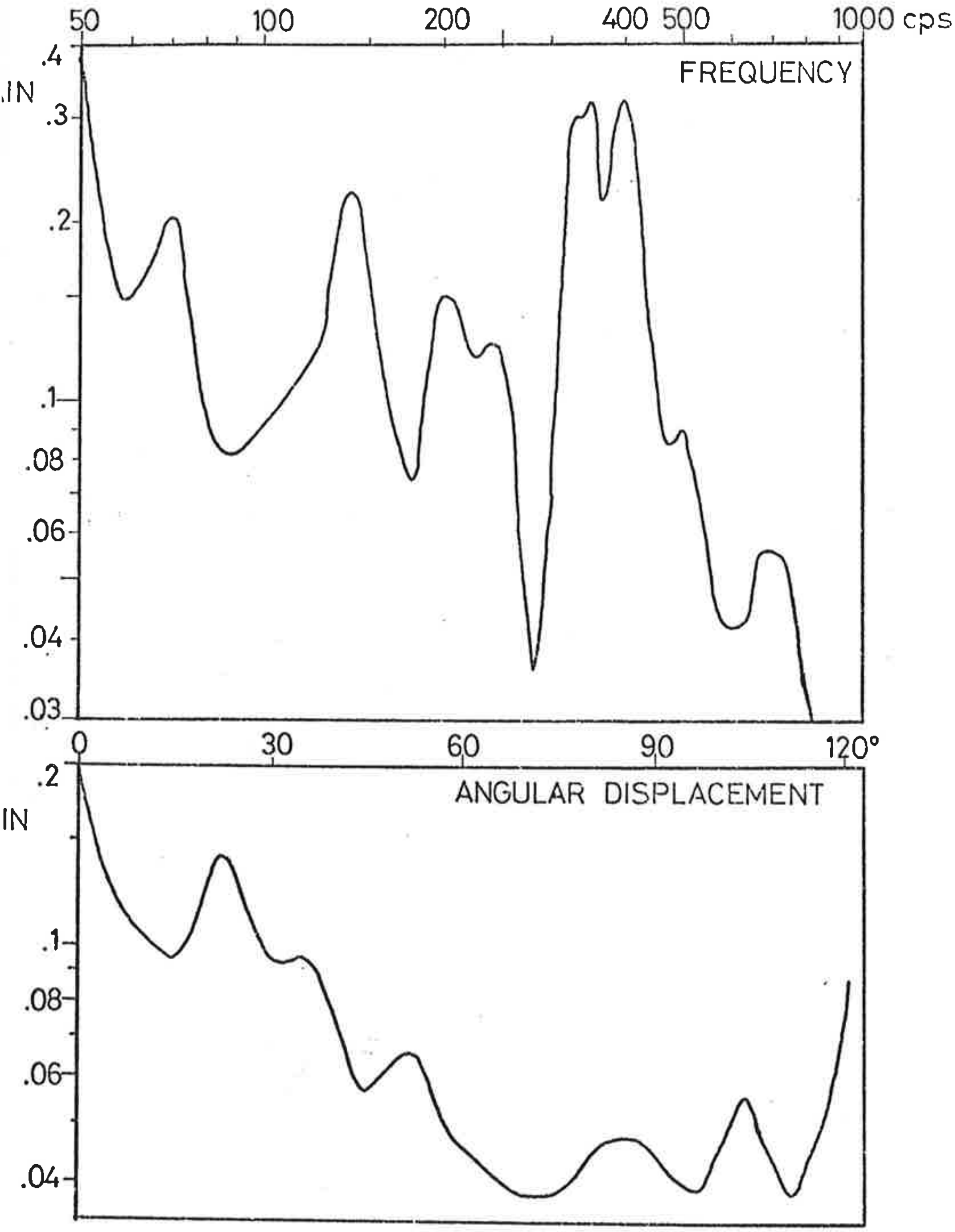



FIGURE 5. VARIATION OF RESPONSE ACROSS THE TIRE WITH FREQUENCY AND INPUT-OUTPUT ANGULAR DISPLACEMENT

Nodal patterns

Testing for nodal patterns

The way in which a tire vibrates and the combination of circumferential, diametral and tangential modes, cannot be easily modelled analytically. Some analysis has been made for the overall tire vibrations as related to vehicle ride, and in the relations between suspension and tire characteristics (Ref. 3 ). Also, there exists some mathematical models of tires (Refs. 4 ,5).

It was felt that a visual approach would reduce the complications of using such elaborate models, while at the same time providing insight into the patterns of vibration. Various methods of visualization were tried. The first consisted of attaching bristles (e.g. velvet, paint-brush hairs, carpet) to the sidewall of the tire in such a way as to produce patterns similar to those of a field of tall grass being agitated by the wind. A second method consisted of slightly wetting the sidewall with a soap solution. Upon induced vibration the nodes would remain wet while the zones being agitated would dry quicker thus producing the pattern. Also, a method was tried in which the tire was charged electrostatically and attracted particles, some of which would be shaken off in areas of maximum vibration amplitude. None of these methods showed promising results.

The best results by far were obtained by using the sand-pattern analysis first developed by Chladni and applied to turbine blades by Grinsted (Ref. 1 ). To proceed, the wheel is mounted in a heavy vise adapted to hold the wheel in any position (figure 6). A nodal pattern can be constructed by sprinkling sand-like granules on the top sidewall. The vibration disperses the granules on the surface clearing the areas of strong surface vibration and piling up near the nodes. The granules could be observed travelling up small gradients on the tire surface to escape anti-nodes.

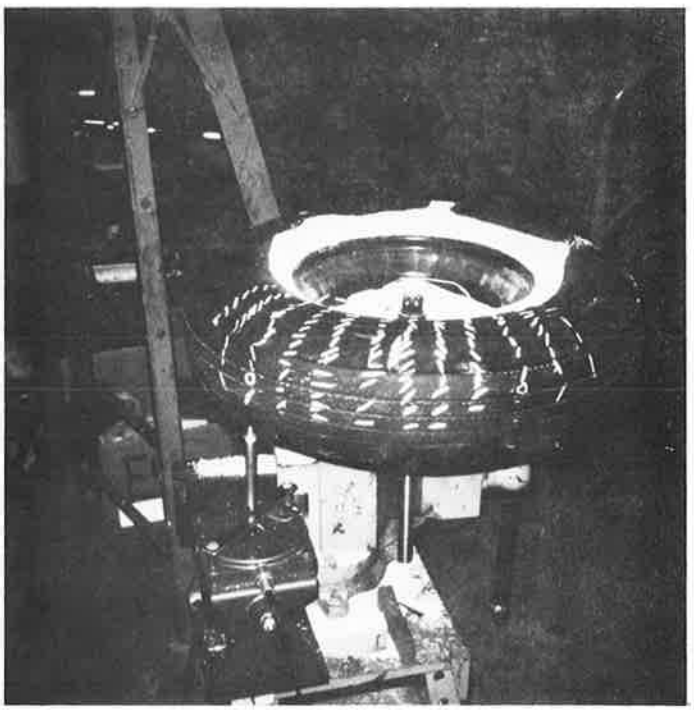


FIGURE 6. VIEW OF APPARATUS FOR NODAL-PATTERN ANALYSIS

Normal components of vibration

The first study involved patterns formed at frequencies in the range of interest (i.e. 200 to 300 cps). It was found that a nodal pattern was formed at every frequency tested, including at those between resonances (i.e. peaks in the amplitude-frequency diagram, figure 5a). As the frequency was increased the number of visible nodes would remain constant up to a point where it would suddenly jump to the next number (Table 1). Some distortion of the pattern did occur (that is, shifting of the nodes) but there was always a full node count (figures 7, 8). The presence of a fault did not affect those shifts appreciably. However, exact location of nodes and anti-nodes by this technique is not possible principally because of the effects of gravity coupled with tire-wall curvature on the motion and final position of the granules.

Tangential components of vibration

The second study involved the discovery of the influence of the tangential modes on the formation of the patterns. Up to then, the patterns were assumed to represent the effects of circumferential and diametral modes alone. Checking the nodal pattern with an accelerometer held in various directions with respect to the surface of the tire, it was found that the antinodal zones of the pattern carried large components of tangential acceleration. The directions of maximum tangential acceleration, when plotted on a tire, (figure 9) correspond closely to the nodal pattern for that tire. The presence of a fault did not change the pattern appreciably, as in the first case.

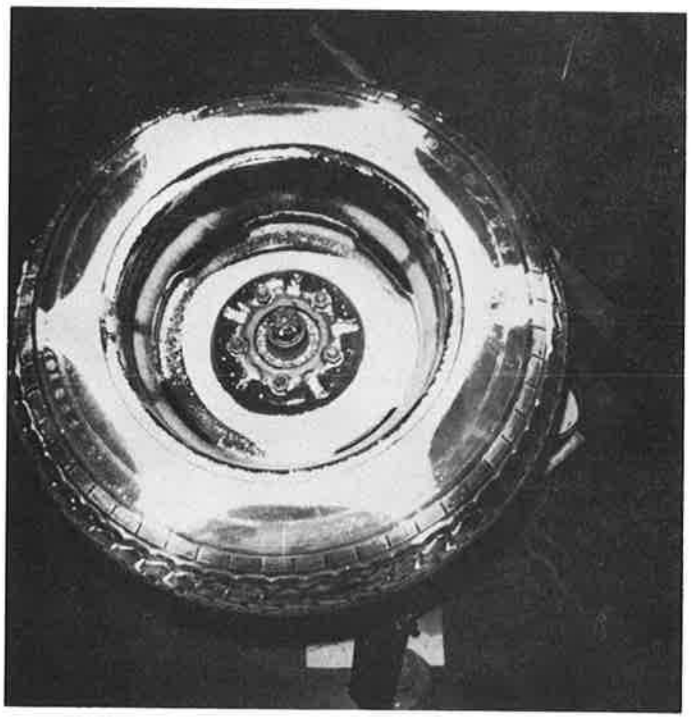


FIGURE 7. SIX-NODE PATTERN, RADIAL TIRE, 151 CPS

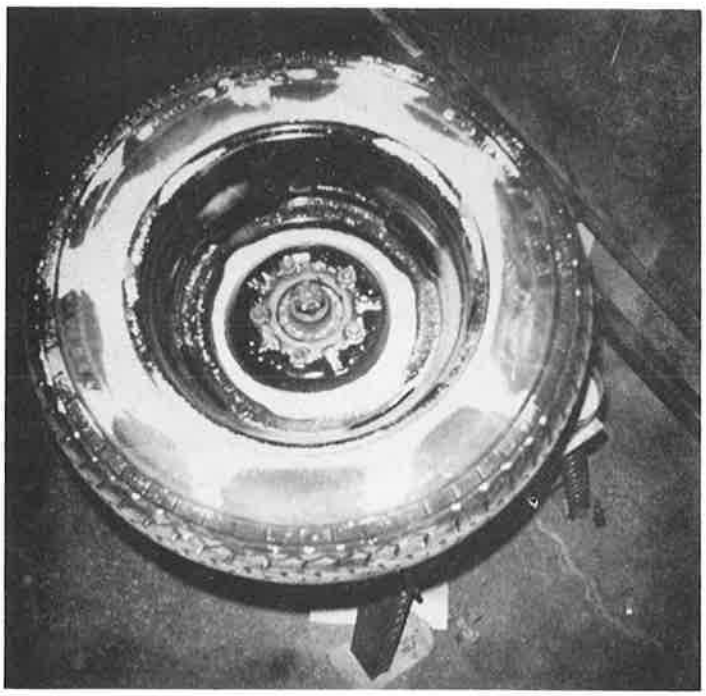


FIGURE 8. TEN-NODE PATTERN, RADIAL TIRE, 190 CPS

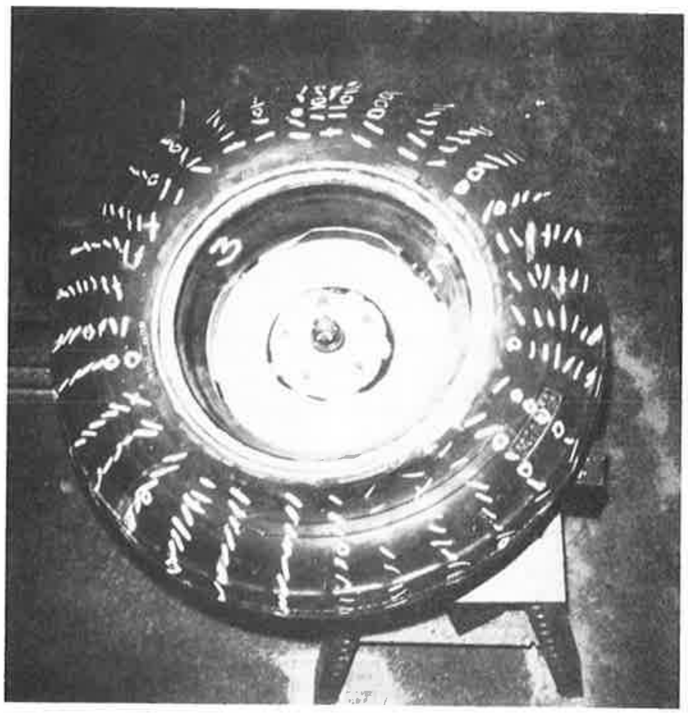


FIGURE 9. TANGENTIAL-NODAL PATTERN, BIAS-BELTED TIRE, 253 CPS*

*Lines show direction of maximum amplitude at each point. Circles indicate nodes.

TABLE 1

NUMBER OF NODES IN NODAL PATTERN FOR INCREASING FREQUENCY

| FREQUENCY | NUMBER OF NODES |
|---|---|
| 256 | 6 |
| 260 | 6 |
| 270 | 7 |
| 275 | 7 |
| 280 | 7 |
| 282 | 7 |
| 285 | 8 |
| 288 | 8 |
| 290 | 8 |
| 300 | 8 |
| 320 | 9 |
| 350 | 10 |

## CHAPTER III
## DESIGN OF TIRE-TESTING SYSTEM

### Design characteristics

The design of the test rig was based on the experiments described above. During the first period of the project a set-up in the Engineering Projects Laboratory of MIT was used. The tire and wheels were mounted in a lathe chuck, with the shaker attached to the tailstock and the accelerometer mounted on a frame near the headstock (figure 10). Adequate results were obtained, but the gearbox of the lathe introduced extraneous noise which swamped the signal.

The test rig was designed to supersede the lathe arrangement and to eliminate the problems encountered in its use. A tire-roll tester borrowed from the Transportation Systems Center served as basis for the apparatus.

The tire-roll tester consists essentially of a channel-beam frame on which the motor and speed control are mounted (figure 11); a side column with a bearing housing for support of the wheel axle; a platform with a motor-driven roller which can be raised hydraulically to put it in contact with the tire; and a cage to encompass the tester. Driving the tire through the roller permits a wide testing range of speeds and loads.

The tire-roll tester was modified in order to accommodate the shaker, accelerometer and other apparatus for response-measurement testing. The vibrator arrangement was mounted on the side column and required three adjusting motions for the experiment: in-and-out and up-and-down on the sidewall, and rotation around the tire.

As presently constructed, the shaker is mounted inside a split cylindrical housing on which it can be made to slide in and out by means of an adjusting screw. The housing is in turn attached to a plate on which it can slide in and out, for a shaker range of about six inches. The plate rests on a pair of rods on which it can slide up and down with another adjusting screw. The rods are held by a

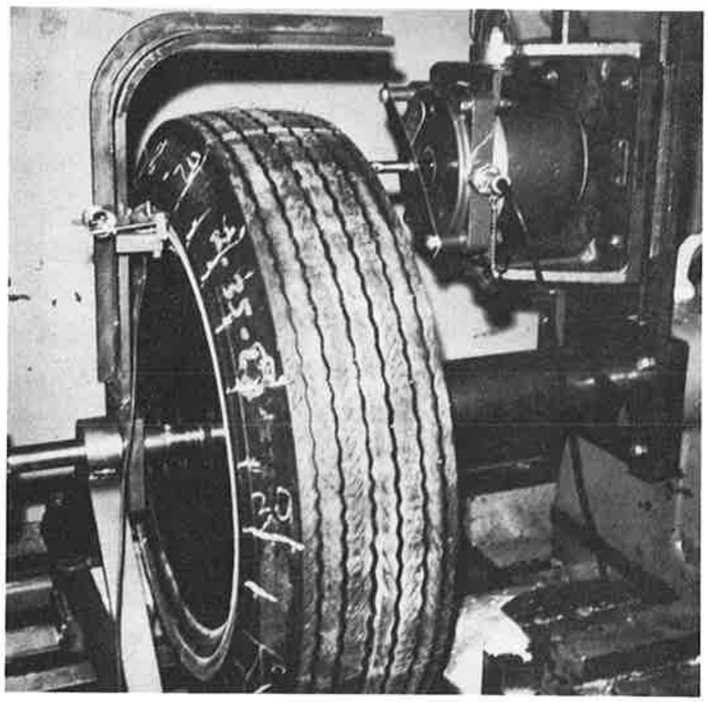


FIGURE 10. VIEW OF RESPONSE-MEASUREMENT APPARATUS MOUNTED IN A LATHE

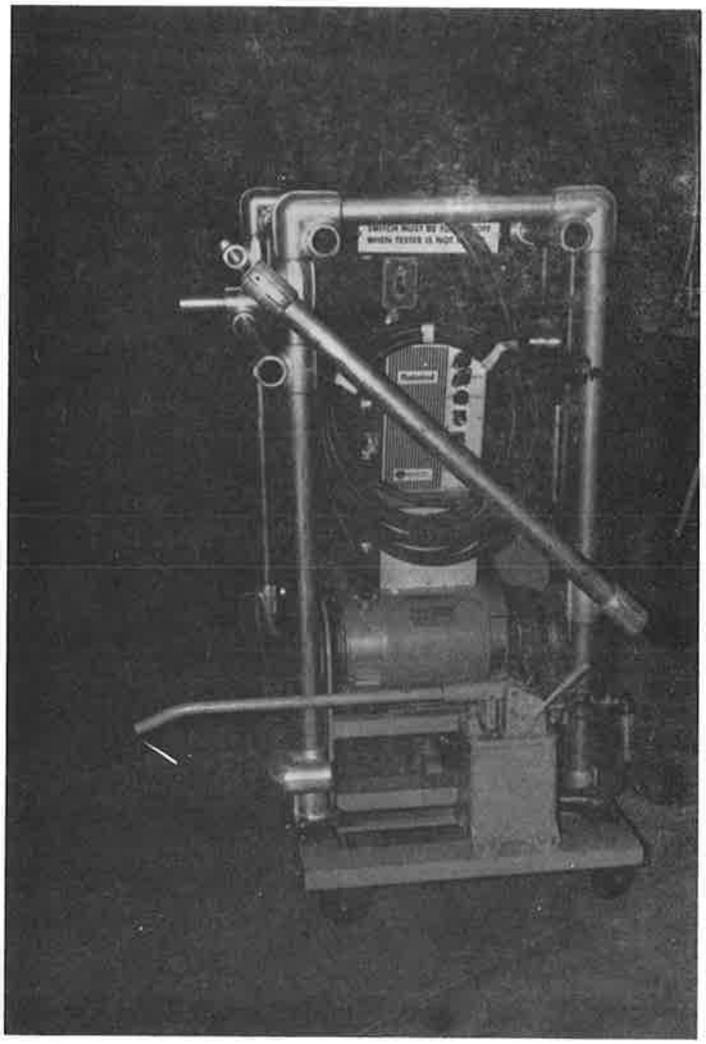


FIGURE 11. TIRE-ROLL-TESTER FRAME

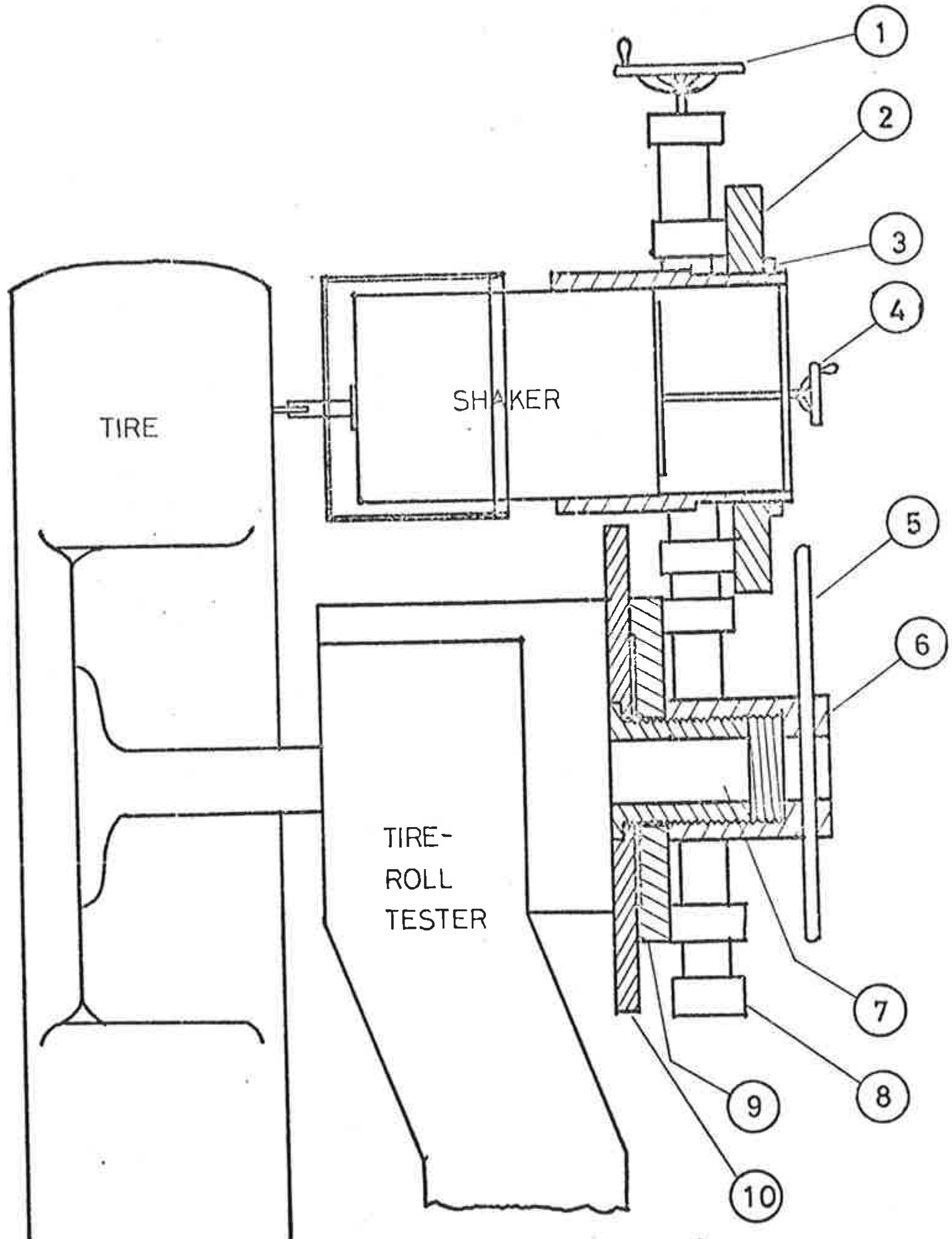
similar plate mounted on a cylindrical shaft concentric with the wheel axle and held by a threaded cup. By releasing the cup the assembly can be rotated around the tire. The shaft is fixed against the side column making a rigid assembly between the vibrator and the tire-roll tester. The shaker transmits its vibration to the tire through an auxiliary suspension and a small wheel, (figures 12, 13, 14).

The detector is mounted on the opposite sidewall, (figure 15), It consists of an accelerometer attached to a small frame that comes in contact with the tire through a rolling wheel. The frame has to be supported so that it can follow closely the surface of the tire in order to minimize the effects caused by irregularities in the surface of the tire. This means an effort to eliminate friction or slip-stick effects from the support. This is met by the use of a cantilevered frame and flexural bending pivots (figure 16). A diaphragm air cylinder is used to provide for initial contact loads because of its low friction and sensitive response. The detector assembly is attached to the cage built of two-inch pipe (figure 17).

## Equipment used

The apparatus set up is shown in figure 18 and described in figure 19. The auxiliary apparatus included the following:

- signal generator 5 hz to 10,000 hz (Hewlett Packard HP-200$C_D$)
- 250-watt amplifier (MIT EPL 0588)
- Ling 50-lbf shaker with auxiliary-suspension attachment
- Accelerometer
- High-impedance amplifier (Ithaco 255)
- Band-pass filter (5 hz to 10,000 hz) (Ksonhite 312)
- Oscilloscope (Tektsonix 502-A dual beam)
- x-y recorder (time and A.C. registers) (Moseley 2D2)




1 Adjusting screw
2 Back plate
3 Housing ring adjustment
4 Adjusting screw
5 Cup handle
6 Threaded cup
7 Threaded shaft
8 Counterweight
9 Assembly support plate
10 Assembly support plate

FIGURE 12. DIAGRAM OF INPUT SIDE OF TESTER

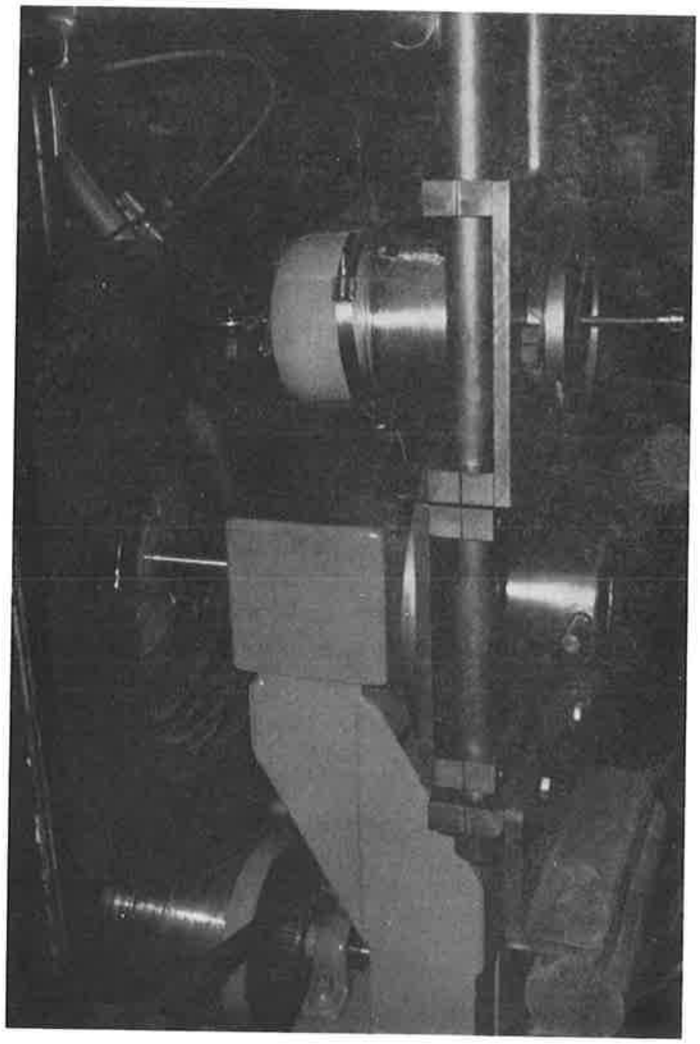


FIGURE 13. CLOSE UP OF SHAKER IN CONTACT WITH TIRE

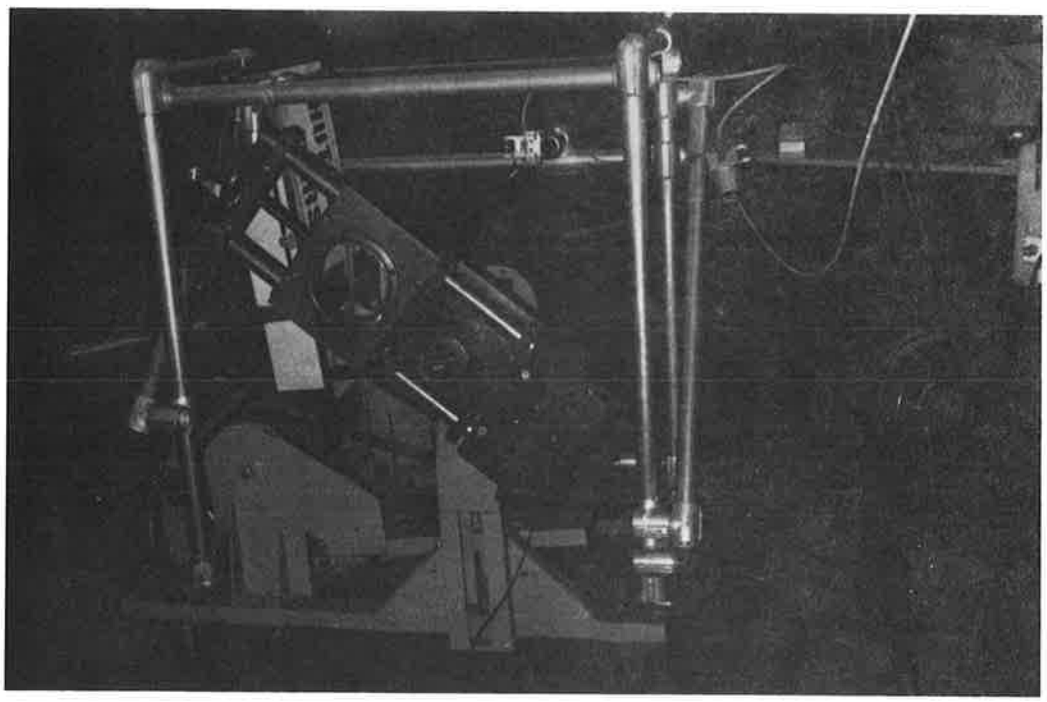


FIGURE 14. VIEW OF INPUT SIDE DISPLACED FROM ZERO POSITION

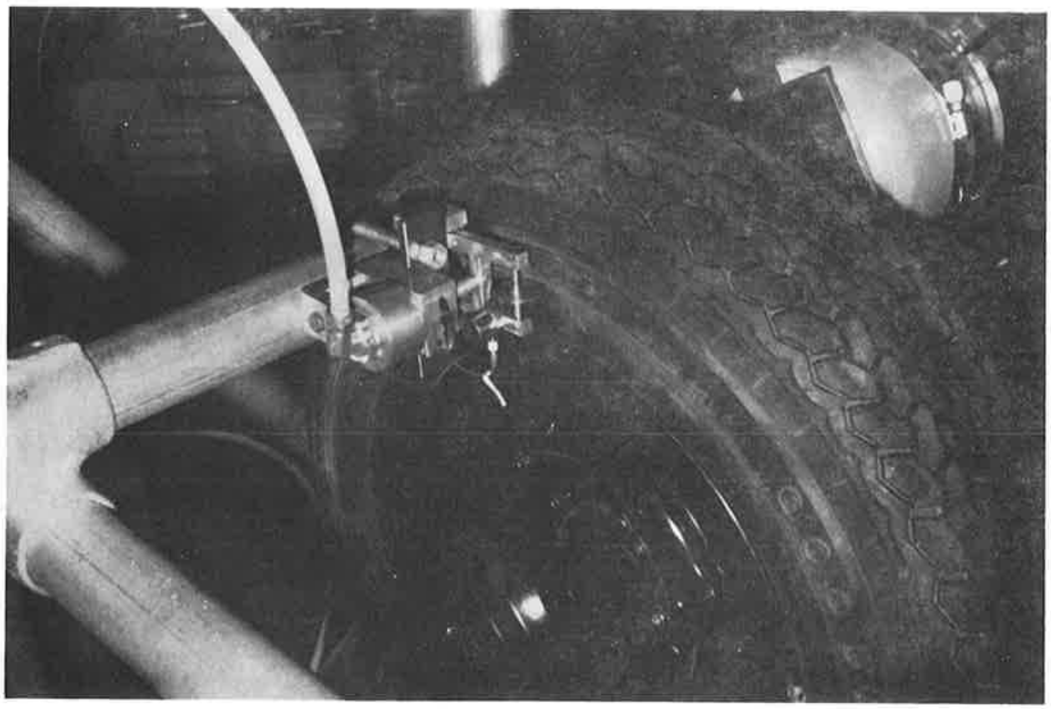


FIGURE 15. OUTPUT SIDE SHOWING DETECTOR

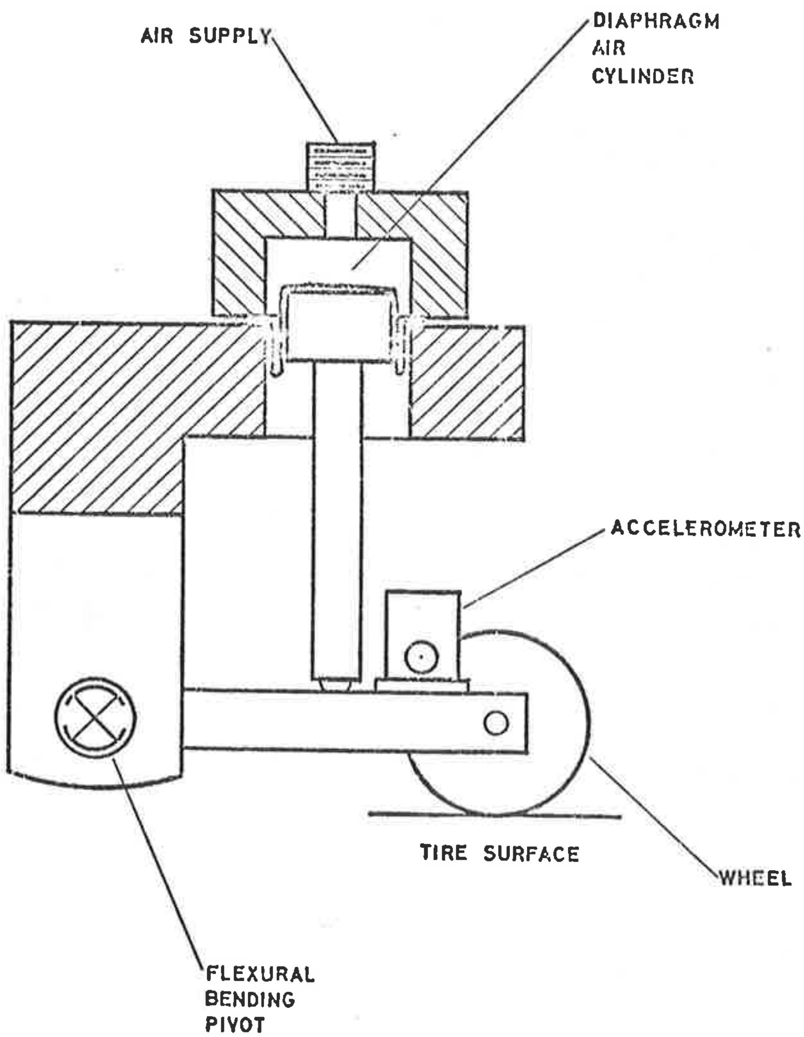



FIGURE 16. DIAGRAM OF DETECTOR ARM

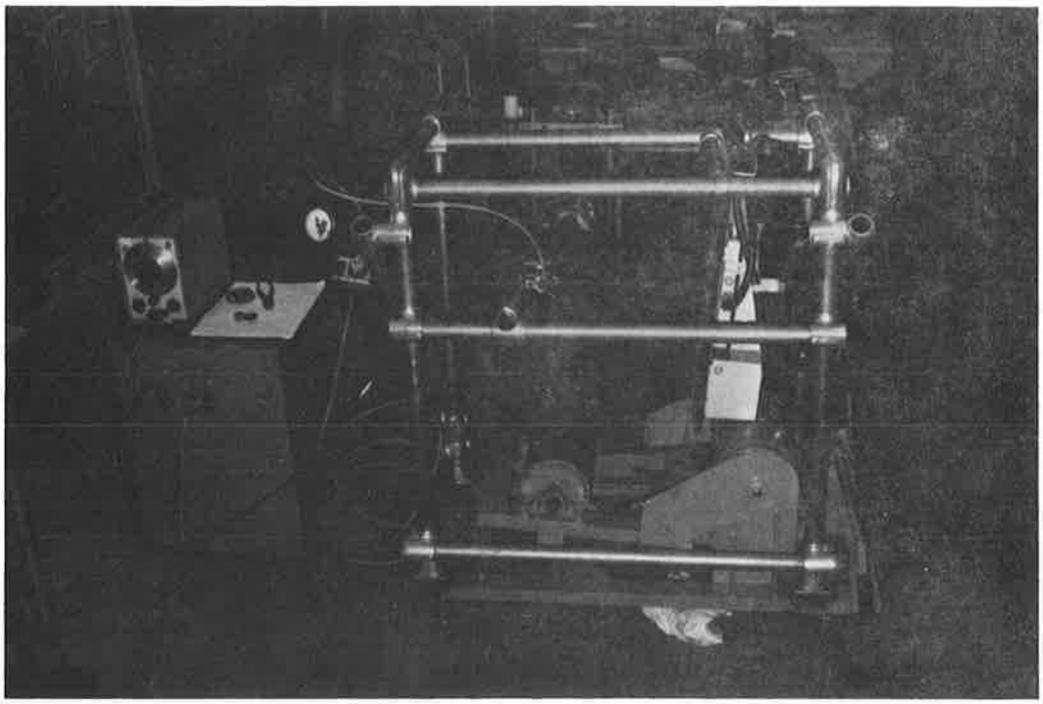


FIGURE 17. POWER SUPPLY AND TIRE-ROLL TESTER

The parts added to the existing tire-roll tester were the following:

- Parts shown in figure 12
- Parts shown in figure 16
- Cage of two-inch pipe shown in figure 17

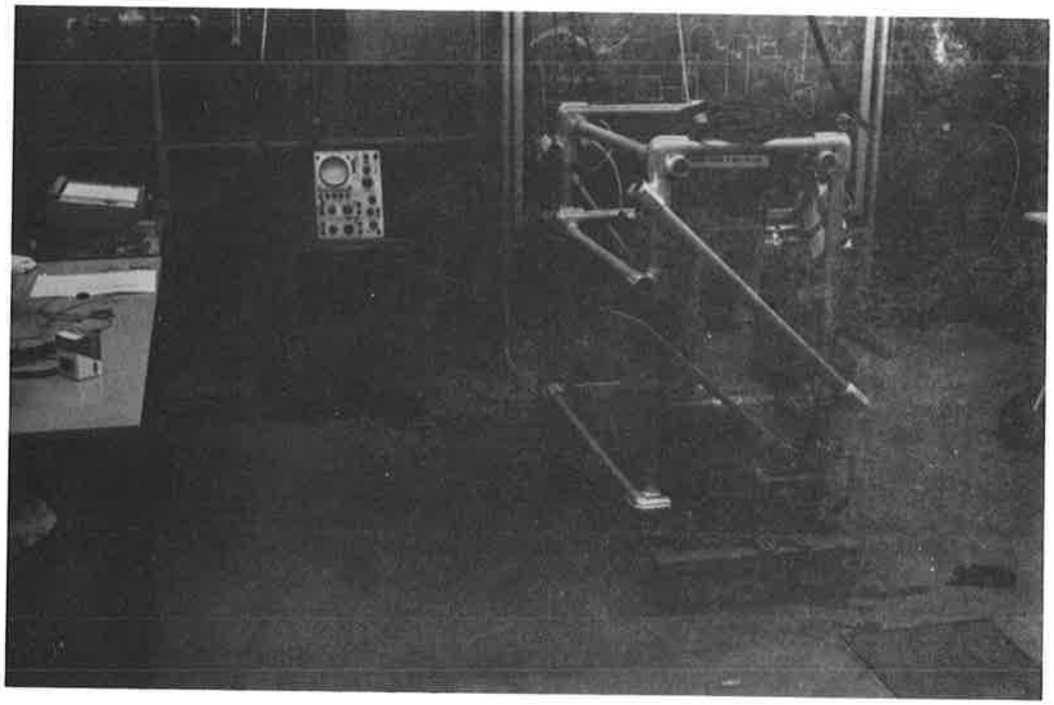


FIGURE 18. VIEW OF EXPERIMENTAL SETUP

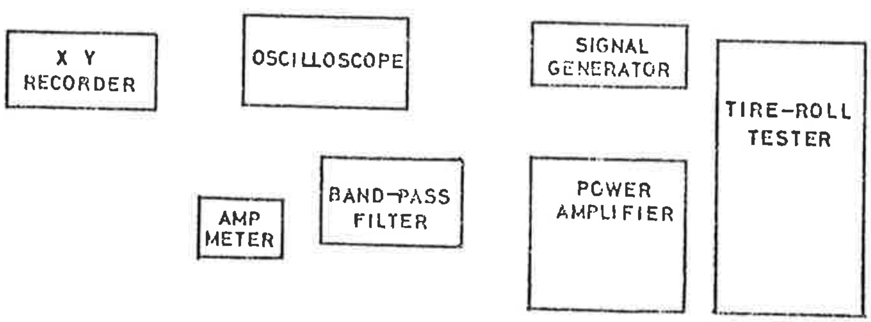



FIGURE 19. KEY TO FIGURE 18

## CHAPTER IV

## TEST RESULTS

### Testing procedure

The testing was carried out on tires provided by the Transportation Systems Center. Specially prepared cuts and disbonds (separations between the plies) were used to represent faults and their behavior was contrasted against sound tires of similar construction.

The procedure for each testing run consisted of mounting the tire on the rig, inflating it to its desired pressure, and adjusting the roller pressure. The next step was to adjust the positions of the vibrator and the detector on the surface of the tire. For most of the experiments, they were located at the center of the sidewall on opposite sides of the tire; however, for determination of circumferential nodes this relative position had to be varied.

In the test rig as presently developed, the positioning of the vibrator is handled by means of the adjusting screws, the force of application being regulated by the auxiliary suspension of the shaker. The position of the detector is also set by two adjustments. The parallel bar (figure 4) regulates the height of the detector on the sidewall, while the crossbar adjusts to the width of the tire. Once the detector is placed, air pressure is provided to the diaphragm air cylinder according to the application force desired for the test.

The following steps depended on the variable being measured. Generally, a resonant frequency was first established (i.e. a combination of frequency and input-output angular-displacement settings). In the test program various types of tires were tested with different kinds of faults at different pressures and speeds of rotation.

### Influence of faults

The results of the experiments are summarized in figures 20 to 24, which represent typical traces of the response across the tire for different conditions of testing.

The first effect studied was the behavior of the equipment with sound tires to examine its characteristics. As mentioned above, the previous experimental setup failed to give adequate results due to external noise and to the inefficient output-arm response to surface imperfections (bumps or depressions). The external noise in the test rig is now minimal, but traces of the depressions present in the sidewall of some tires still appear (figure 20). In this figure, the tire tested had depressions in both sidewalls (2 in. long x 1/4 in. maximum depth) and their presence can be detected from the trace. A tire without depressions did produce a smooth signal (figure 21).

The second effect studied was to try to establish the relationship in magnitude between these traces and the traces of a faulty tire. Figure 22 shows a trace for a tire with three disbonds and depressions in both sidewalls. These disturbances all leave traces in the graph but are distinguishable from each other only because of previous knowledge of their positions. Also present are other disturbances whose origin can not be identified.

The following steps in the course of the experiment were undertaken to try to refine these results and to eliminate the undersigned signals from the output.

It was found, for example, that exciting the tire at different frequencies would alternately eliminate one or the other depression trace (figure 23). Similarly, by varying the force of application of the detector on the sidewall different effects became noticeable. For a radial tire, increase in application force meant an increase in noise; for a bias-belted tire increase in application force meant a reduction in the effect of a depression in the output graph (figure 24). Also, small surface imperfections (e.g. letters for identification of the tire) are not noticeable in the response except under conditions of zero application force.

Increasing the speed for rotation of the tire worsened the effect of surface imperfections, as was expected, but even decreasing the speed to a very low level did not eliminate the effects of the depressions.

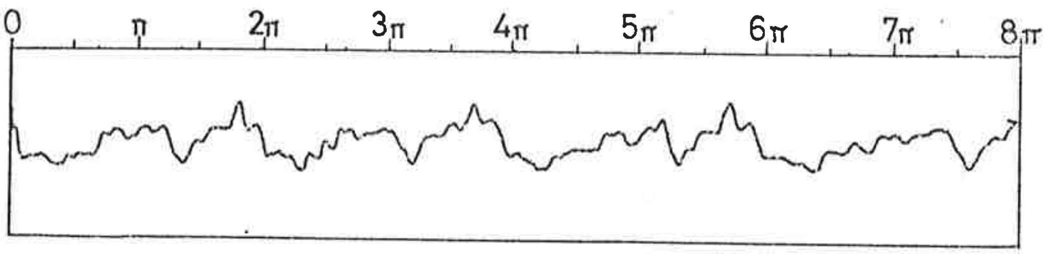



FIGURE 20. OUTPUT TRACE FOR A SOUND TIRE WITH SIDEWALL DEPRESSIONS (4 REVOLUTIONS OF THE TIRE)

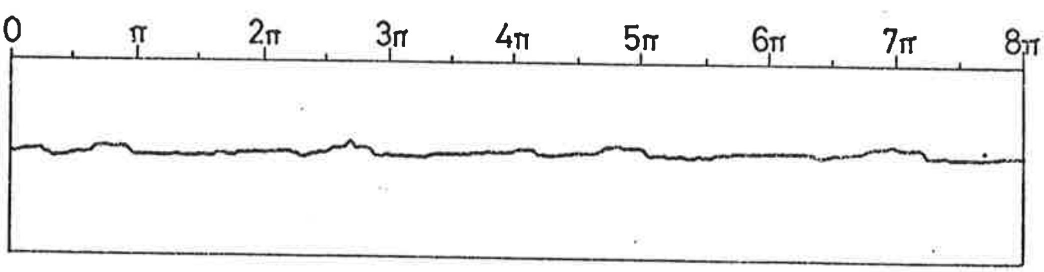



FIGURE 21. OUTPUT TRACE FOR A SOUND TIRE WITHOUT SIDEWALL DEPRESSIONS (4 REVOLUTIONS OF THE TIRE)

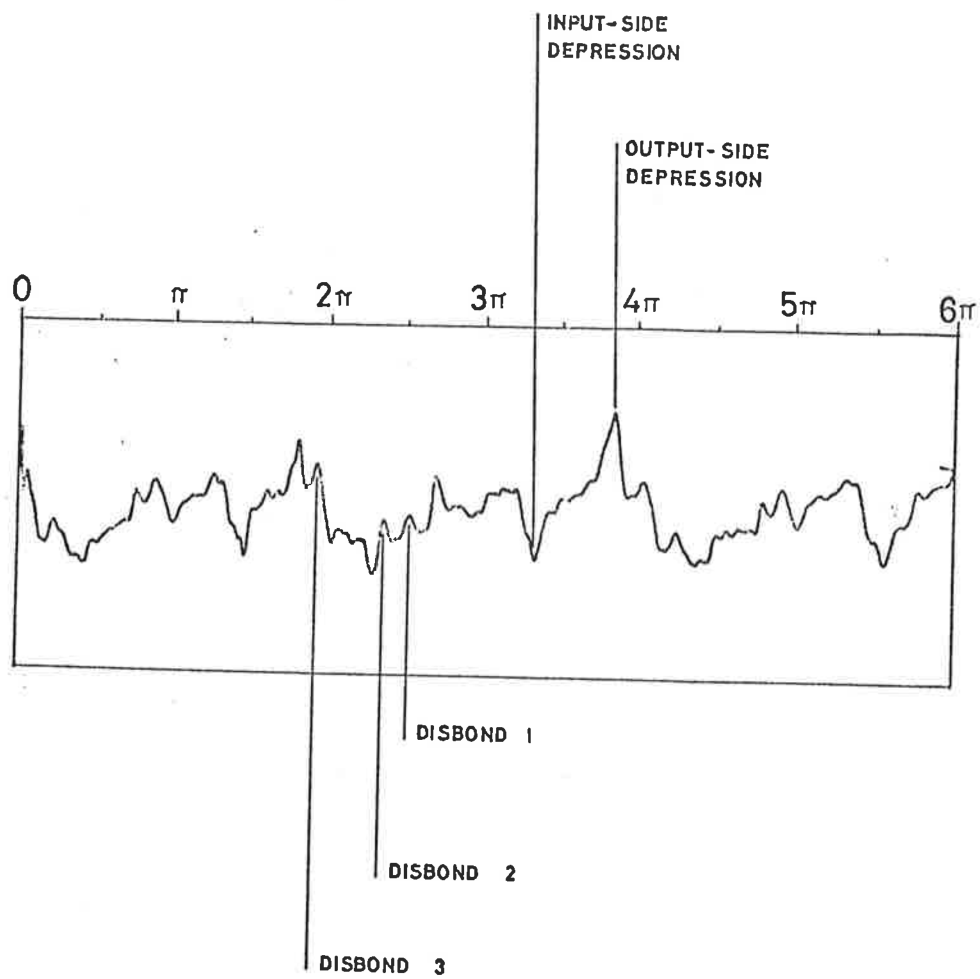



FIGURE 22. OUTPUT TRACE, BIAS-BELTED TIRE WITH PREPARED FAULTS (3 REVOLUTION OF THE TIRE)

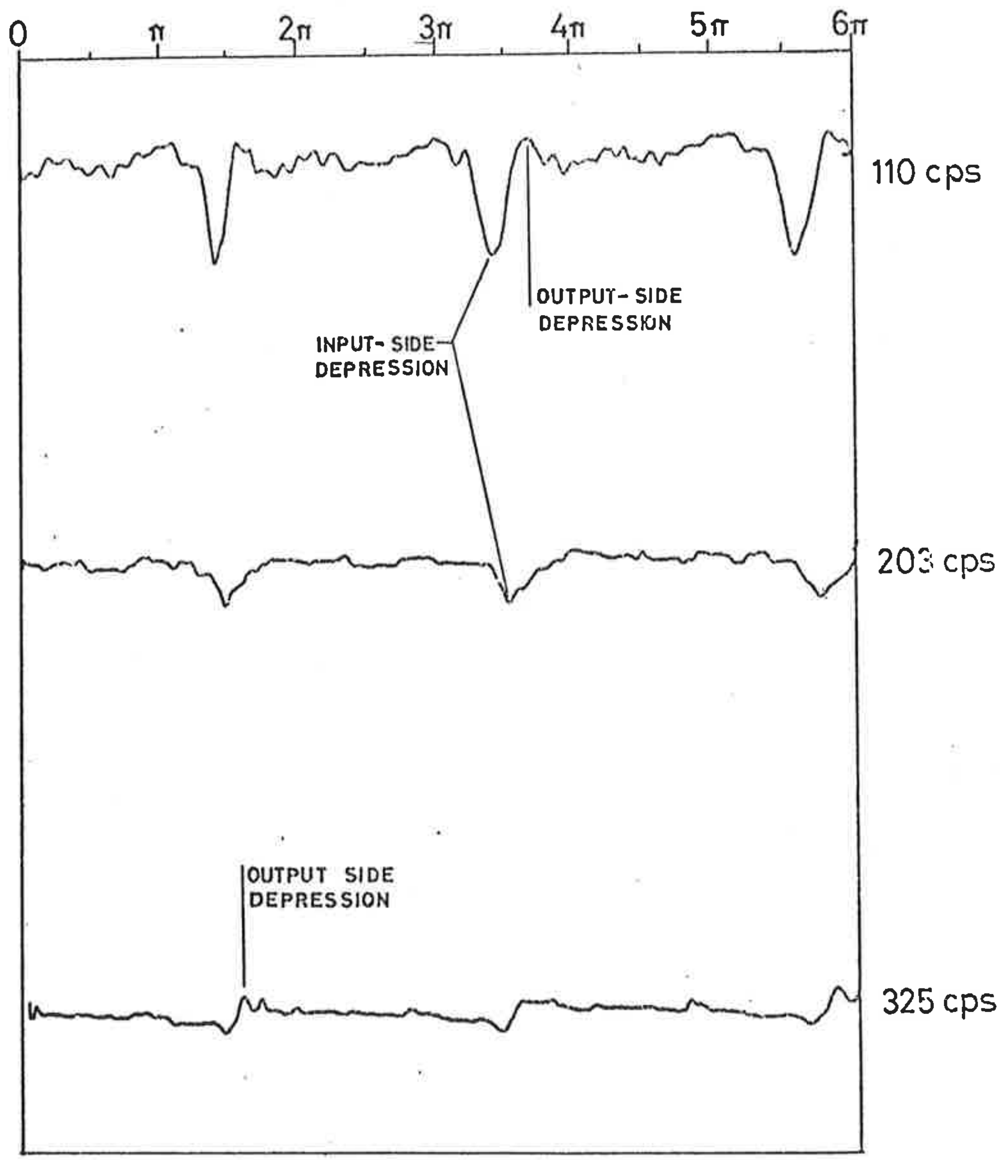



FIGURE 23. OUTPUT TRACE FOR DIFFERENT FREQUENCIES, BIAS-BELTED SOUND TIRE (3 REVOLUTIONS OF THE TIRE)

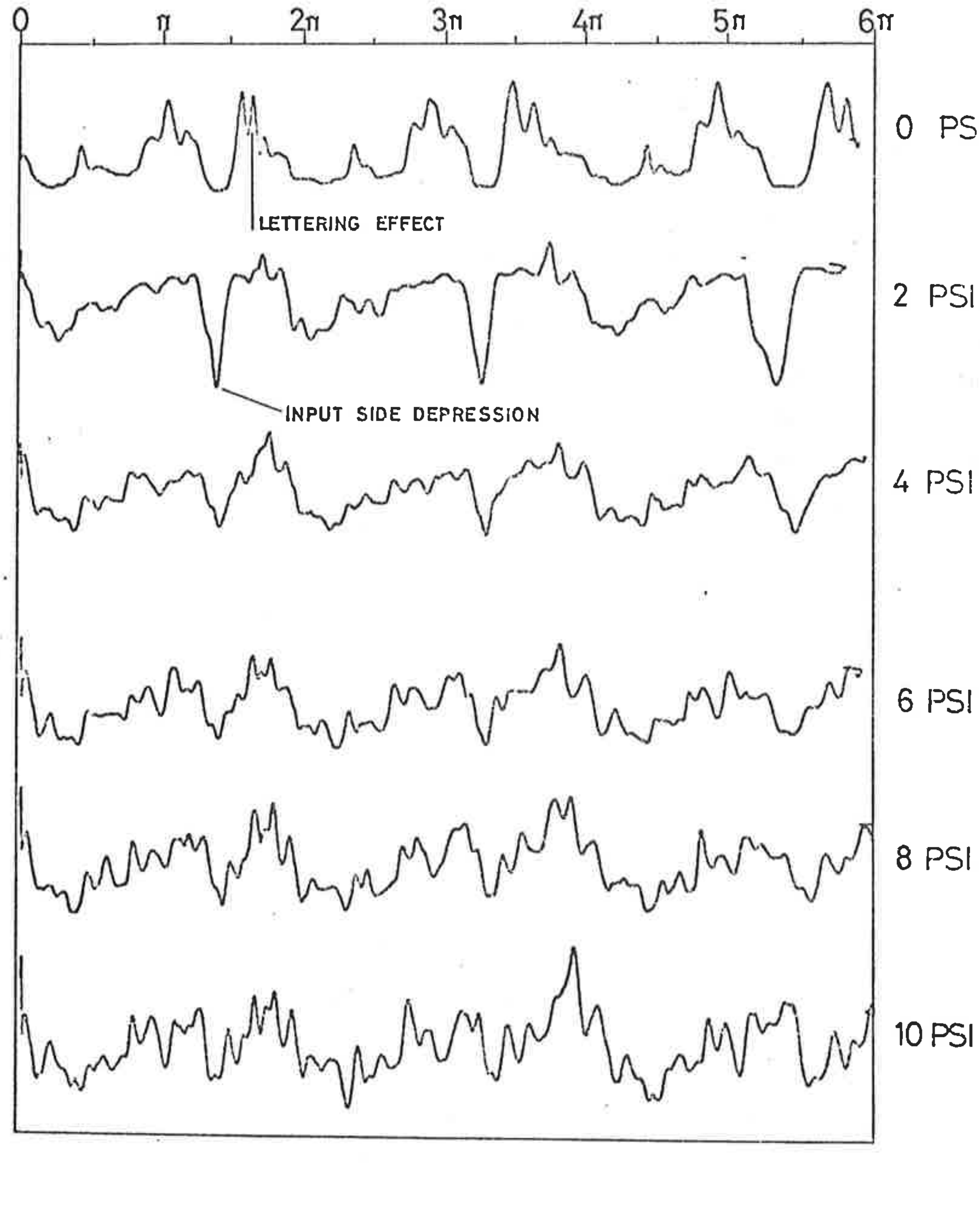



FIGURE 24. OUTPUT TRACE FOR DIFFERENT APPLICATION FORCE LEVELS OF THE DETECTOR (3 REVOLUTIONS: 1 PSI EQUIVALENT TO 1 lbf OF THE TIRE)

## Desirable improvements

Two factors are suggested as possible cures for these undesirable traces. The first and more feasible relates to the disturbance in the pattern of vibration input to the tire due to the presence of a surface imperfection. This occurs because of the variation in shaker force with armature position in the core. Consultations with the shaker manufacturers failed to produce a simple suspension arrangement to eliminate this effect. The recommended method is a feedback controller unit which would regulate the vibration input to the tire by varying the current input to the shaker according to the displacement of the plunger in the core. This would assure a constant force-amplitude input level. As the project ran out of funds there was no possibility of purchasing or manufacturing such a controller.

The second factor is related to the detector. Attempts were made to reduce damping and to increase the natural frequency of the detector arm to above the frequencies being measured.

The design and construction of the arm were undertaken after funds had run out, and no debugging tests were subsequently possible. It seems likely that the natural frequency is in fact too low and could be raised without great difficulty.

Another factor, closely related, is the possibility that the variations in the output trace may be caused by imperfections in the tire and rim contact in the bead area. Two possible ways in which this could be an important variable are: first, since the vibrator and the detector are fixed in space, an imperfect seat would mean additional material between input and output, which will produce a change in the vibration pattern. Second, an imperfect contact may change the nature of the node assumed to exist in the bead for a circumferential mode of vibration, also affecting the response across the tire.

## CONCLUSIONS

It can be concluded that faults in the tire leave a trace in the vibration response across the tire. In this regard, previous results by Weigl stand up. But it has also been shown that various other disturbances of the tire, which may not be faults, also leave traces of comparable magnitude.

We have identified possible mechanisms which could be responsible for the raise (principally the nonlinearity of the shaker and the poor impedance match of the detector). The exhaustion of funds prevented simple measures being taken to investigate these mechanisms and to apply corrective measures.

While it is just possible, therefore, that in Weigl's original work the changes in surface shape caused by defects were responsible for the strong signals obtained, it is more likely (since Weigl was aware of this possibility) that the nonlinearity of the present shaker is the principal cause of the noise.

In sum, the methodology adequately detects faults in a tire, although not in sufficient detail as to identify them. A more refined apparatus, including some modifications mentioned above, should discriminate results in a more adequate manner and isolate the effects of the faults or make them identifiable.

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## APPENDIX A

## INSTALLATION AND OPERATION OF TIRE-ROLL TESTER

### To install

1. Connect signal generator to audio amplifier.
2. Install ampere-meter between audio amplifier and shaker. Maximum-current-allowed tables are in shaker instruction manual.
3. Install pressure gauge in air line. Recommended scale zero-20 psi. Equivalence: 1 psi equals 1 lbf application force of detector.
4. Install accelerometer on the detector arm.
5. Connect accelerometer to the high-impedance amplifier. Set gain to 30-40 db.
6. Connect band-pass filter between output of high-impedance amplifier and oscilloscope.
7. Install X-Y recorder. Set Y axis to record A. C. value of output signal. Set X axis to time.

### To operate

1. Mount the tire on the tester.
2. Position shaker input on the sidewall using adjusting screws. Positive contact between vibrator wheel and the tire must be assured for all the circumference of tire. For coarse contact adjustment the housing ring (figure 12, no. 3) may be loosened to move the entire shaker housing. After tightening the ring, the adjusting screw (figure 12, no. 4) may be used for fine contact adjustment.
3. Position detector output on the sidewall. Only loose contact with the tire is required.

4. Connect air pressure to output arm. Important: do not connect air pressure to output arm unless it is in contact with the tire, and similarly, do not remove output arm from the side-wall before disconnecting air pressure.
5. Start rotation of the tire.
6. Set frequency of excitation.
7. Set vibration input. Check amp-meter for current level.
8. Adjust input-output displacement.
9. Start X-Y recorder.