

Performance Evaluation of the UMTRI Tire/Wheel Uniformity Test Machine

Final Report

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One outgrowth of UMTRI's Truck Tire/Wheel Systems Research Program has been recognition of the need for a truck tire uniformity test machine capable of measurements to at least 50 Hz. This report provides an overview of the design and initial testing of a prototype machine recently constructed at UMTRI for this purpose.

The machine utilizes a drum that is 67.23 inches in diameter, driven by an electric motor capable of speeds from 0 to 60 MPH. The face of the drum is 24 inches wide so that dual wheel assemblies can be tested. It accepts complete truck tire/wheel assemblies, making it possible to test tires, wheels, and hub components in single and dual wheel configurations. The force and moment variations of the rotating tire/wheel assembly are measured by solid state strain gage transducers. The force signals are transformed to the frequency domain for evaluation of the individual harmonic amplitudes.

Ten tires in the 11-22.5 size range were tested on the machine for comparison against measurements from other uniformity test machines. The good agreement obtained is one indication of the UMTRI machine's validity. Spectral maps of each of the tire force and moment properties were also prepared to provide a more critical view of the machine's dynamic behavior. At 31 Hz a lateral resonance is seen in the spectral maps due to lateral resonance of the machine on its foundation. Lateral force, aligning torque, and overturning moment measurements near this frequency are not valid due to the resonant amplification. Radial force and tractive force measurements are unaffected and are valid from 0 to 50 Hz. A resonance due to compliance of the spindle is observed near 55 Hz, and certain resonances are seen in the 30-40 Hz range, which are believed to be related to the tire/wheel assembly.

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The author acknowledges the help of a number of people at UMTRI who contributed to the construction and test of the UMTRI Tire/Wheel Uniformity Test Machine.

- Mr. Chris Winkler designed and supervised construction of the machine, drawing on his considerable ingenuity to develop a machine within a very limited budget.

- Mr. Mike Hagan (with consulting help from Mike Sayers) designed the data acquisition and analysis systems.

- Dr. Lu Xiao-Pei is appreciated for his help in calibrating the transducers and testing the ten tires for the project.

- Mr. Ashok Gouri kindly contributed his time in performing data analysis from the tire tests.

Performance Evaluation of the UMTRI Tire/Wheel Uniformity Test Machine

Introduction

In 1979, the Motor Vehicle Manufacturers Association (MVMA) in cooperation with the Rubber Manufacturers Association (RMA) initiated a research program at The University of Michigan Transportation Research Institute (UMTRI) to investigate the truck ride effects resulting from nonuniformities in the tire and wheel components. Phase I of the program was an experimental investigation of the cyclic force variations produced by nonuniformities in tire/wheel assemblies. An MTS Model 860 Tire Uniformity Machine was provided by RMA for the tire and wheel component measurements. Other phases of the project examined the way in which these cyclic forces act on a truck to produce vibrations and ride degradation.

The findings from the project are presented in three reports addressing the areas of :

- 1) The relationship between nonuniformities (runouts, imbalances, etc.) in tire/wheel components and the cyclic forces that are produced [1].
- 2) The way in which force variations in tire and wheel components couple to the vehicle to excite ride vibrations [2].
- 3) A methodology and results of a vehicle test whereby the ride degradation caused by excitation from individual nonuniformities (different harmonics, wheel positions, and combinations) were assessed [3].

In the tire and wheel testing in Phase I, the usable bandwidth of measurement was limited to 20 Hz as a result of resonances in the cantilevered transducer of the MTS Tire Test Machine. The studies of truck ride degradation indicated significant sensitivity up through 30 Hz (4th harmonic of the tire), the maximum frequency tested at that time. Thus nonuniformity measurements over an adequate frequency range were not possible with the existing machine.

Lacking a test machine capability to measure tire/wheel nonuniformities over the frequency range of interest, in the 1983/84 fiscal year MVMA, RMA, and UMTRI agreed that the remainder of the available funds (supplemented by a University contribution) should be used to build and test a new machine. In addition, the Akron-Standard Company, a manufacturer of tire test equipment, supplied a 67-inch road wheel to the project at their cost. The hardware was designed and constructed during the 1984 and early-1985 calendar years. The funds provided were sufficient to complete the construction, but did not cover an evaluation of its performance. The evaluation, including test of ten tires, was performed in the summer of 1985. This report presents an overview of the machine capabilities observed, and compares the tire test results with previous work.

Description of the UMTRI Tire Test Machine

Because of the limited budget, it was necessary for UMTRI to build a very basic machine, incorporating only the essential features to achieve measurement capability. Only two parts of the machine are unique—the tire carriage/transducer system, and the road wheel. For instrumentation, an UMTRI digital data acquisition system is used, and for driving the road wheel, an electric drive was borrowed from the Honda/UMTRI Motorcycle Tire Dynamometer.

Road Wheel/Drive System - The road wheel is a 67.23-inch drum purchased from Akron Standard. The drum is 24 inches in width to allow testing of truck dual wheel assemblies. It is driven by a 75 HP electric motor with a speed control to maintain the desired test speed over the range of 0 to 60 MPH.

Carriage/Transducer System - As seen in Figure 1a, the carriage/transducer system is a fabricated structure, built by UMTRI. A government-surplus lathe bed is installed to provide a rigid guideway for the carriage. Outriggers are added to the lathe bed to increase lateral stiffness. The carriage holds the transducer system with the tire/wheel hardware, and loads the tire against the road wheel under hydraulic control. The carriage is designed to accommodate single-wheel hardware fitting a Rockwell FF-931 wheel spindle, and dual-wheel hardware fitting the Rockwell R-170 rear spindle.

Six discrete transducers are used, supporting the wheel spindle at both ends for maximum rigidity (thus ensuring a maximum usable frequency range for the machine). On the outboard end of the spindle, X and Z direction transducers are mounted, as shown in

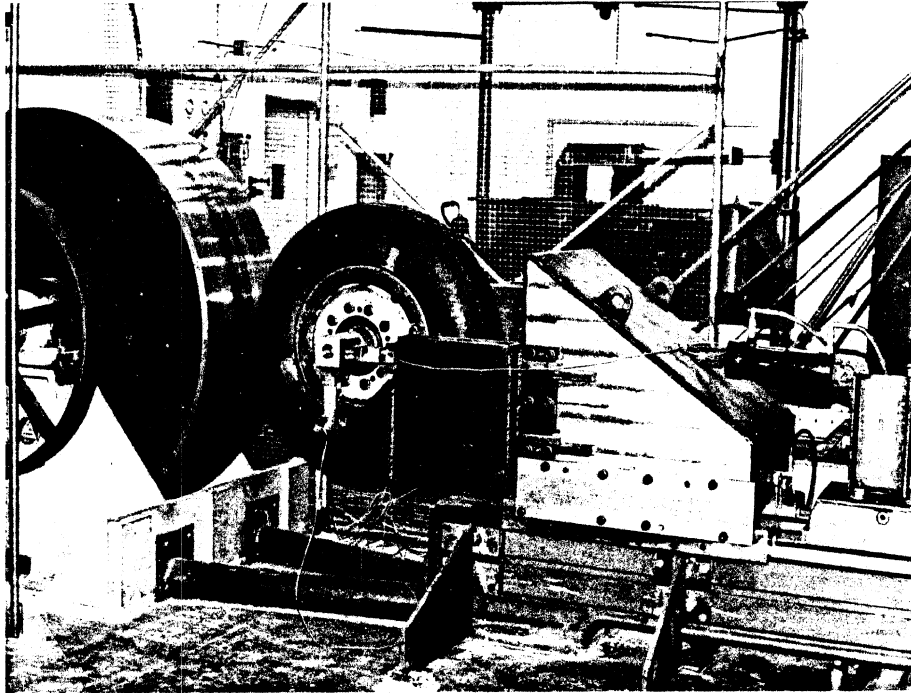


Figure 1a. UMTRI Tire/Wheel Uniformity Test Machine.

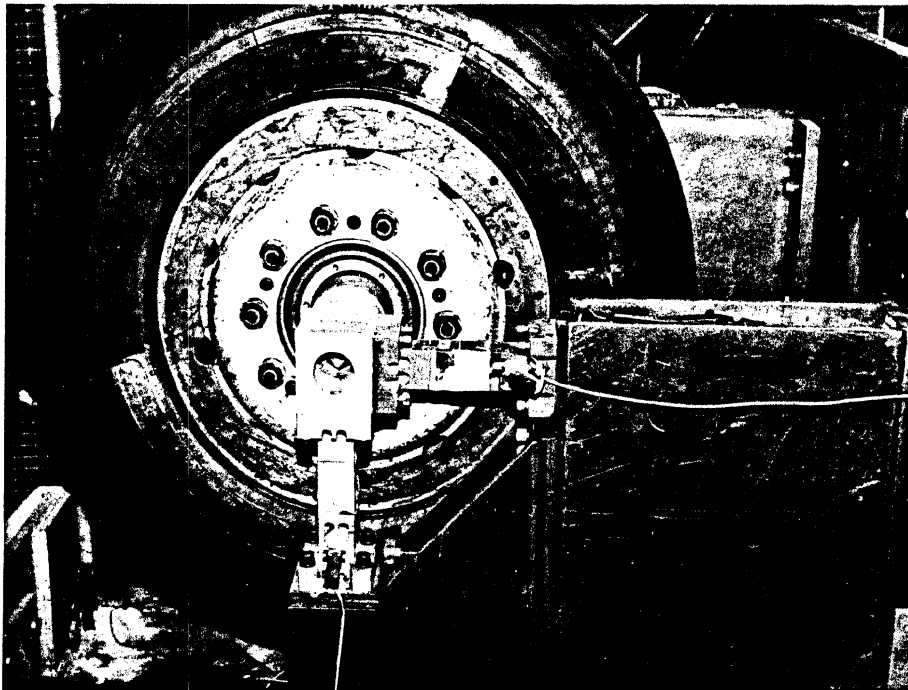


Figure 1b. Close-Up of Force and Moment Transducer.

Figure 1b. The mounting at the inboard side of the wheel incorporates four transducers-- one for the tractive force (X), one for the lateral force (Y), and two for the radial force (Z). The two inboard transducers in the Z-direction are needed to react against the rolling moment without inducing bending moments in the force transducers. All transducers are of a common design, based on shear strain elements with the shear measured by Kulite semiconductor strain gages. Semiconductor gages provide the high signal levels necessary to resolve forces of a few pounds in the presence of static loads of many thousands of pounds, while yet allowing the stiffness necessary in the transducer to keep machine resonances in the range of 100 Hz or more.

Wheel rotation is measured with a photo-detector producing one pulse per revolution. Funding was insufficient to allow development of hardware for measurement of runouts at this time.

Instrumentation - In recent years UMTRI has developed state-of-the-art digital data acquisition systems (DDAC). For test purposes, a DDAC is connected to the tire test machine, measuring the signal levels from all force transducers along with the wheel rotation signal. These signals are sampled on a time base (at 250 samples per second) and written on a 64-megabyte cassette tape. The tape is later read on an IBM-PC for data processing. Using a "calibration matrix" determined during the calibration of the machine, the individual load cell signals are transformed into the three forces and moments at the tire contact patch (based on the SAE tire force and moment conventions). The data are then processed using a fast Fourier transform (FFT) to obtain the spectrum of the three forces and three moments. The spectrum is further processed to obtain the amplitude for each harmonic. Separate measurements of the imbalance forces (a test in which the wheel is brought up to 60 MPH and retracted from the drum) allows correction of the first harmonic values for the imbalance component.

Comparison with Other Machines

As a means to provide a direct evaluation of the UMTRI machine performance, ten tires used in previous test programs were re-tested for comparison to previous measurements. Tubeless tires of the 11-22.5 size were selected as follows:

<u>Manufacturer</u>	<u>Type</u>	<u>RMA No.</u>
General	Bias	15
Firestone	Bias	23
Goodrich	Bias	39
Uniroyal	Radial	56
Goodrich	Radial	62
Uniroyal	Radial	75
General	Radial	85
Firestone	Radial	91
Goodrich	Radial	92
General	Radial	95

The tires were mounted on a precision wheel accurate to within ± 0.002 inches at the bead seats. Radial tires were inflated to 90 psi, and bias tires to 85 psi. The tires were loaded against the drum to 5400 lb radial load. After warm-up for approximately 20 minutes, each was tested at speeds of 5 to 60 MPH, making measurements over a period of at least 8 revolutions. A separate balance test was conducted to determine the imbalance of the overall tire/wheel assembly.

The digital records of the transducer forces receive a multiple-step processing by which the digital levels are converted to forces in engineering units, transformed to forces and moments in the tire contact patch, and transformed into the spatial frequency domain by a fast Fourier transform. At this point, the force spectrum may be plotted (as will be shown in the next section) or processed to determine the equivalent sine-wave force amplitude at each harmonic of the tire. The sine-wave amplitudes are the equivalent of the harmonic force magnitudes which would be obtained on conventional uniformity test machines.

The first harmonics of radial force, lateral force, tractive force, and aligning moment were extracted from the 5 MPH test records for comparison to previous measurements. The comparison of the radial forces (F_z) is shown in Figure 2. For each data point the horizontal axis represents the measurement obtained on the UMTRI machine, while the vertical axis indicates measurements from other machines. The solid diamond symbols are earlier measurements (by UMTRI) using the MTS machine. Also plotted along the ordinate are the data values provided by RMA for these tires, as measured on machines owned by the tire manufacturers.

For six of the tires the radial force variations measured on the UMTRI machine are virtually identical to those measured earlier on the MTS machine. Three others fall below the line of equality by 20 to 38 lbs. For these tires, the UMTRI machine measured larger forces which may be due in part to the fact that the UMTRI transducer is much stiffer than was the MTS transducer (a stiffer transducer measuring a higher magnitude of force variation). Additional factors could also be responsible. A difference in bead seating between the measurements on the MTS and UMTRI machines may be responsible for some of the disparity in the radial force values. Also on the MTS machine, there was considerable mechanical cross-coupling between the lateral and radial force directions, such that lateral force components could either add or subtract from the observed radial force variation, depending on the relative location of their maximum points on the circumference of the tire. For example, the tire with the largest radial force difference (38 lb) also has the largest lateral force variation as measured on the UMTRI machine (39 lb). The lateral force variation is also very close to 180 degrees out of phase with the radial force variation, thus it would have tended to reduce the observed radial force magnitude on the MTS machine.

One tire stands out as having a much lower radial force variation on the UMTRI machine in comparison to the MTS machine. The tire produced 55 lb on the UMTRI machine, while it was 144 lb on the MTS machine and 73 lb on the RMA machine. This tire had one of the larger lateral force variations, which could have contributed to the high reading on the MTS machine, because the lateral force variation is closely phased with the radial. Thus the two would add due to mechanical cross-coupling on the cantilevered transducer of the MTS machine. Other factors could be bead-seating differences, as well as simple errors in procedure.

The comparisons with the RMA measurements show larger discrepancies. This is expected because the RMA measurements were made on the different machines owned by

COMPARISON OF MTS AND RMA MACHINES TO
UMTRI MACHINE

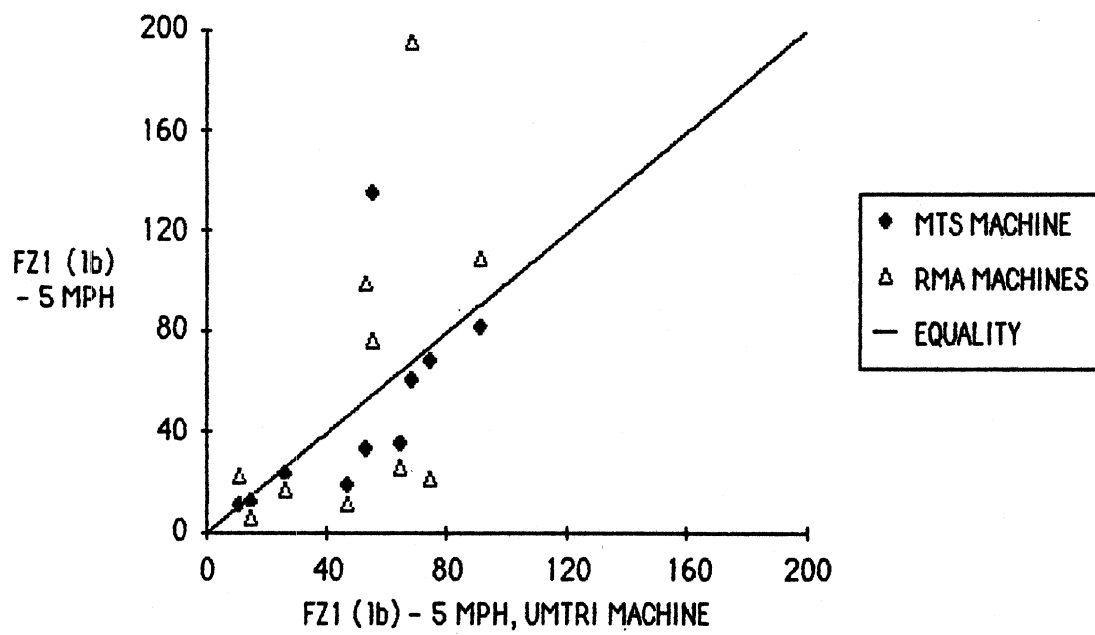


Figure 2. Comparison of first harmonic radial force measurements.

the separate tire manufacturers. The same errors were observed in the earlier project [1] and they do not imply inaccuracies in the UMTRI machine.

Figure 3 shows a comparison of the first harmonic lateral force variations (F_y) measured at 5 MPH. Comparing the MTS and UMTRI machines, the majority of measurements agree within 10 lb, with the largest error of 31 lb (31 lb on the UMTRI machine versus 62 lb on the MTS machine). Considering the tire mounting variations, and the mechanical cross-coupling present on the MTS machine, this level of agreement is probably as close as may be expected. Shown also on the plot are data for the RMA composite lateral force variation (first harmonic data are not available). The RMA values are generally higher in magnitude, as would be expected for the composite measurements.

Figure 4 shows a comparison of the first harmonic tractive force variations (F_x) measured at 5 MPH on the UMTRI and MTS machines. Although the scatter appears large, note that the plotting scale only goes up to 8 lb. The largest difference is just over 4 lb, with most of the readings within 2 lb. This is considered very good agreement.

Figure 5 shows a comparison of the first harmonic of aligning torque (M_z) variations. Both machines obtain measurements that are within 30 to 50 in-lb, with the exception of one tire which measured 222 in-lb on the MTS machine. This is the same tire which was anomalously high in the radial force measurement. The high aligning moment value would suggest the possibility that the tire is prone to bead-seating variations. Otherwise, the agreement in aligning torque measurements are reasonable.

Overall, the comparisons that have been made indicate that the UMTRI machine performs properly in low-speed measurements of tire uniformity. In effect this confirms that the transducers are measuring the forces and moments intended, and are properly calibrated. A more critical and comprehensive picture of the machine's performance is obtained by examining its dynamic characteristics.

Dynamic Characteristics

By choosing time-based data acquisition and processing methods on the UMTRI machine, it is possible to obtain a very comprehensive picture of the machine's dynamic characteristics in the course of the normal test routine. Additionally, the data provide a picture of the dynamic behavior of the tire. On the UMTRI machine the force data are

COMPARISON OF MTS AND RMA MACHINES TO
UMTRI MACHINE

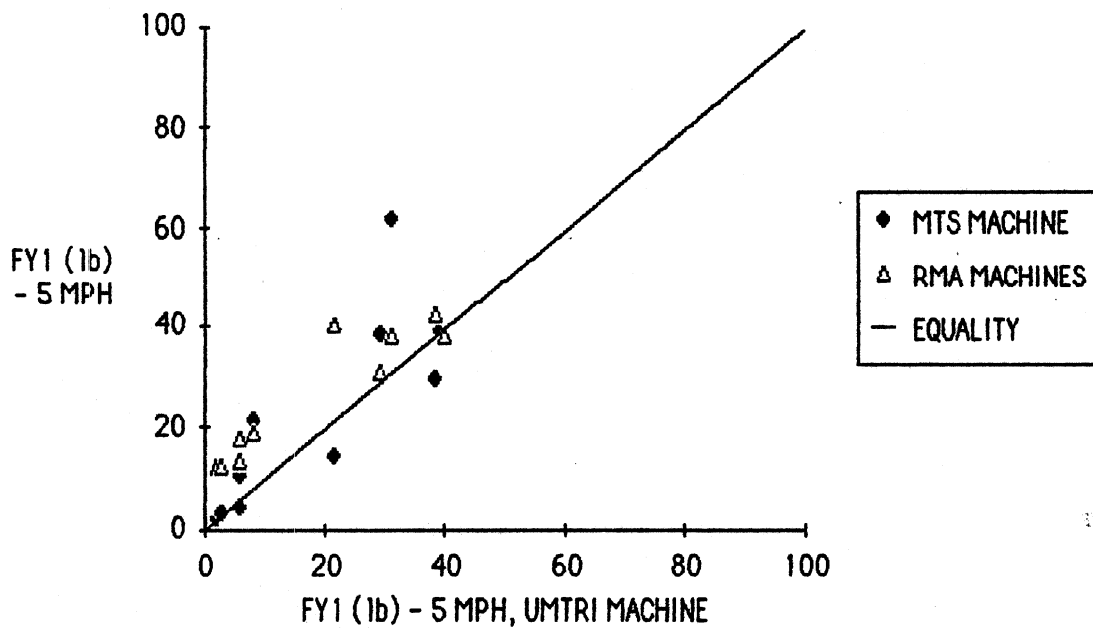


Figure 3. Comparison of first harmonic lateral force measurements.

COMPARISON OF MTS MACHINE TO UMTRI MACHINE

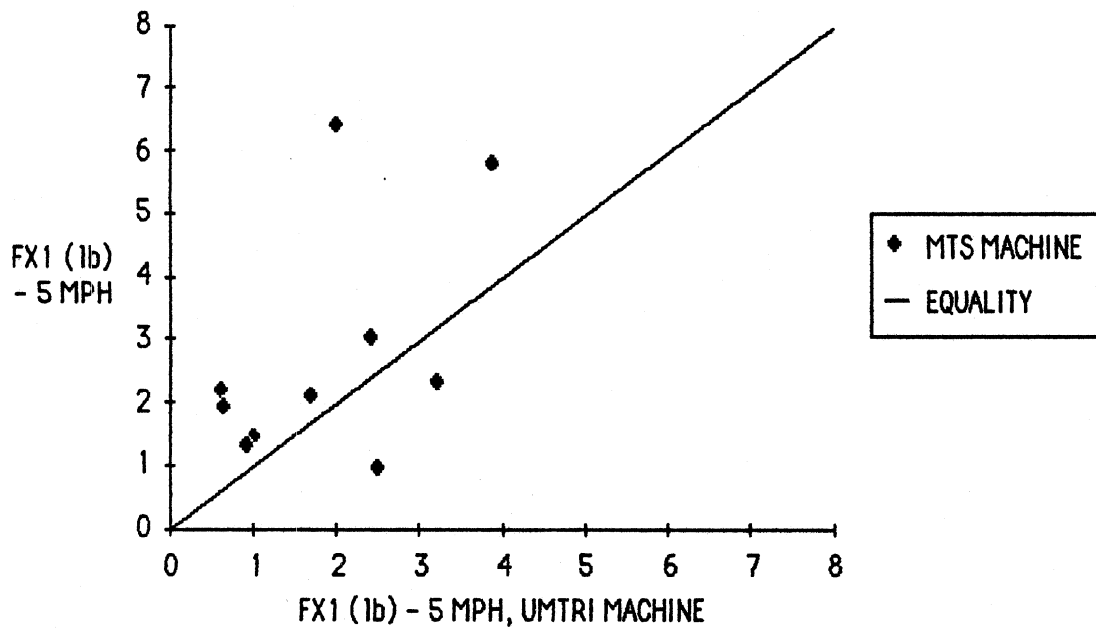


Figure 4. Comparison of first harmonic tractive force measurements.

COMPARISON OF MTS MACHINE TO UMTRI MACHINE

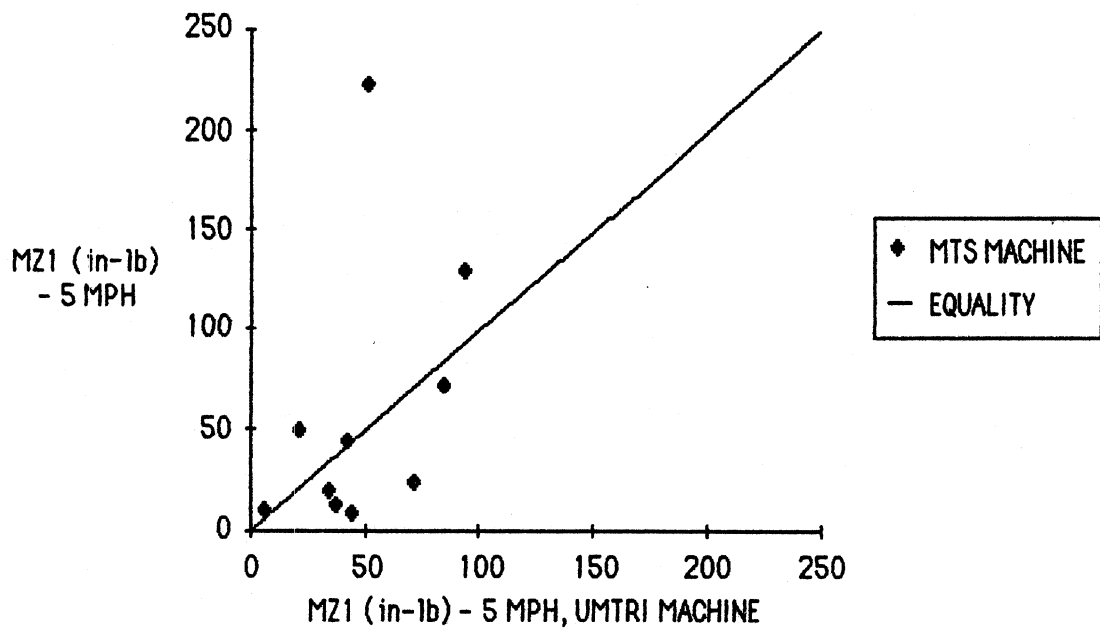


Figure 5. Comparison of first harmonic aligning torque measurements.

sampled on a time base (rather than sampling at specific increments of tire rotation, as on other tire uniformity test machines). Time-base data can be reduced to spectral plots which show not only the tire force magnitudes, but all other force signals present at the same time (electronic noise, machine resonances, etc.).

Tests were made on all tires over the speed range of 5 to 60 MPH at speed increments of 2.5 MPH. For one tire the force measurements were reduced to a spectral map as a means by which to visually illustrate the behavior of the machine and the tire. A spectral map is simply a common plot of all spectra in which each spectral line is offset with respect to neighboring lines, and hidden lines are eliminated.

Radial Force Direction (Fz) - Figure 6 shows a spectral map of measurements in the radial force direction. The vertical scale is force amplitude, while the horizontal scale is frequency. Each spectral line reflects a different test speed, beginning at 5 MPH with the first spectral line. Each succeeding line is 2.5 MPH higher in speed, and the last line corresponds to 60 MPH. The spectral peaks radiating as rays from the front left corner of the plot are forces that change frequency with test speed. These are caused by the rotating tire assembly, and are thus labeled T1 through T12. Spectral ridges that remain at a fixed frequency (for example, like that near 55 Hz) are dynamic resonances of the hardware.

In this format, any nonuniformity in the drum will be seen as additional spectral rays on the plot. The first harmonic (labeled D1) is the largest and is due to eccentricity. It falls to the left of the tire first harmonic because the drum rotates at a lower speed. The drum second harmonic (D2), due to ovality, along with the third and fourth become diminishingly small. Because the drum harmonics are separate and distinct from the tire harmonics, their presence in the spectrum does not produce any error in the tire measurements.

The harmonics of the tire can be readily seen and traced out through the twelfth. The first harmonic grows in magnitude with speed, an effect which is expected because of tire/wheel imbalance (which has not been corrected out in these data). The second and third harmonics grow slightly with speed (the second goes from 15 to 21 lb as the speed goes from 5 to 60 MPH, and the third from 8 to 12 lb). The fourth harmonic rises more dramatically with speed, going from 12 to 25 lb over the speed range of 5 to 60 MPH. The higher harmonics rise similarly. Note that this observation provides clarification of the results reported from earlier research. In previous testing the change in radial force magnitude with speed could not be measured on anything above the second harmonic, and

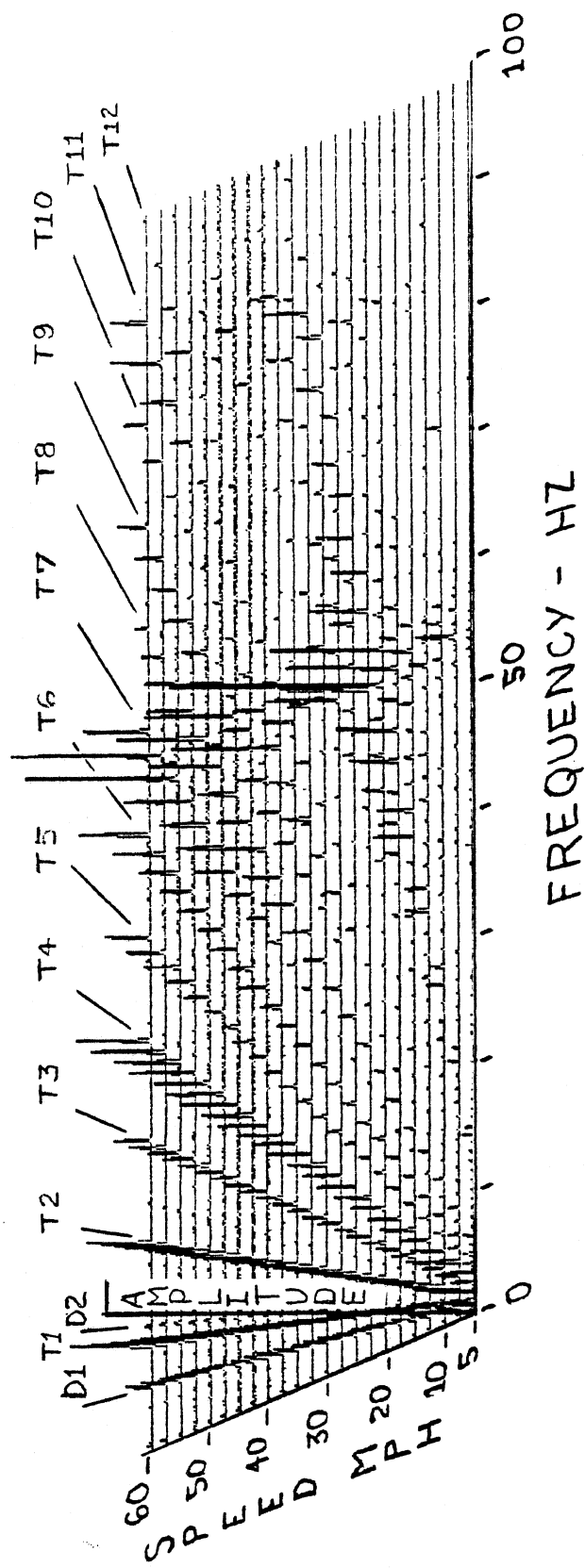


Figure 6. Spectral map of radial forces.

even then the changes with speed could not be separated from machine resonance effects. With the new UMTRI machine, it is now possible to see the exact influence of speed over much of the frequency range.

One limitation that occurs is in the frequency band near 55 Hz. Near that frequency, high spectral peaks are observed. The constancy of the frequency indicates a mechanical resonance of the hardware. From a study of the machine, it has been determined that the resonance is due to radial motion of the wheel on the spindle. It is not possible to stiffen the spindle (its dimensions are dictated by the wheel hardware) so that resonance cannot be eliminated. Although a similar vibration would be present on a truck, it should be noted that 55 Hz is not the frequency at which resonance would be obtained on a truck, because the spindle is cantilevered from the axle on the vehicle, and a lower resonant frequency would be expected.

Aside from the spindle resonance, there appear to be few other significant resonance problems in the radial direction. A possible resonance is indicated around 86 to 90 Hz, but otherwise the machine appears rather clean. Thus, *it is concluded that the machine provides valid radial force measurements over the 0 to 50 Hz range, and from 60 to 85 Hz.*

Lateral Force Direction (F_y) - Figure 7 shows the spectral map of lateral forces plotted on the same amplitude scale as for the radial force map. Only a first harmonic of the drum is evident in the lateral force signal, but it has no effect on tire measurements. Although the map is rather clean, several resonances are evident in the 30-40 Hz range. These are believed to involve lateral resonances of the tire treadband and a machine lateral mode rotating about its attachment on the laboratory floor. (It might be noted that the project resources were too small to allow preparation of a special base for the machine—it is simply bolted to the existing 4-inch concrete floor.) For those resonances that can be tracked to the tire, the force amplification in this frequency range is a quality of the tire and is appropriate to include in the measurements. In the 55-60 Hz range a small resonance is evident, which may be associated with the radial resonance on the spindle. (The spindle is not symmetrical about the tire centerline, thus some lateral motion is possible from the radial resonance.) Near 75 Hz an unidentified resonance is evident.

The lateral force harmonics of the tire are clearly evident through the twelfth. Most tend to be constant with speed except near 30 Hz where they are amplified by the

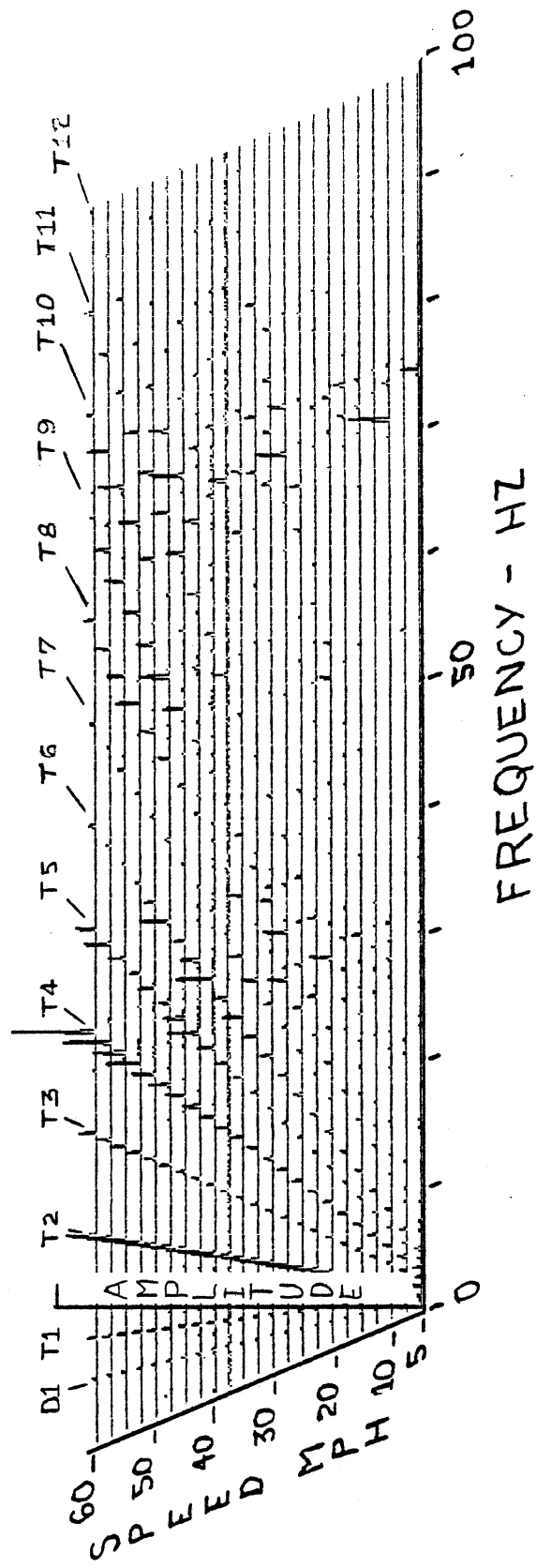


Figure 7. Spectral map of lateral forces.

resonance. From this map *it is concluded that the UMTRI machine is valid for lateral force measurements only to about 28 Hz.*

Tractive Force Direction (Fx) - Figure 8 shows the spectral map of tractive forces, plotted again on the same vertical scale as for radial and lateral forces. As expected, the tractive force harmonics of the wheel are speed sensitive, appearing to grow approximately with the square of the speed. Near 55 Hz the spindle resonance is again visible, because its compliance allows resonance in the tractive-, as well as, the radial-force direction. In the 20-25 Hz range the low-speed tests also show a resonant behavior that is not evident at high speed. This is a new observation that has not been explained. Its speed sensitivity may indicate a torsional resonance of the tire/wheel assembly around its spin axis. The fact that it is speed sensitive makes it probable that it is a tire phenomenon and the effect should be included in the measurements. A 60 Hz (power line noise) is seen in the tractive force signal, although not present in the radial or lateral channels. No specific resonances are identifiable above this frequency. The drum imperfections are evident in the tractive force signal, but again they have no influence on valid measurement. From this spectral map *it is tentatively concluded (pending clarification of the peculiar resonance in the 20-25 Hz range) that the UMTRI machine validly measures tractive force variations from 0 to 50 Hz.*

Aligning Moment Direction (Mz) - Figure 9 shows the spectral map of the aligning moment signal. In the first harmonic range the aligning moment grows strongly with speed as a natural reflection of dynamic imbalance in the tire/wheel assembly. Other harmonics show much lower speed sensitivity, except when they pass through the frequency range from about 28 to 45 Hz. This frequency range is so broad that more than one resonance is involved. The treadband lateral resonances along with the machine lateral mode are undoubtedly responsible for the moment amplification in the 28-36 Hz range, but other resonant modes must also exist in the 36 to 42 Hz range. These modes have not been clearly identified. Note that in the 50 to 60 Hz range there is another small resonance (possibly associated with the spindle compliance), and at 60 Hz there is a low level noise present in the signal due to power line interference. Based on this map *it is concluded that the UMTRI machine measures aligning moment variations validly over the frequency range from 0 to 25 Hz. Its validity in the range of 25 to 100 Hz has yet to be proven when the resonances have been identified.*

Overtuning Moment Direction (Mx) - Figure 10 shows the spectral map of the overturning moment signal. It is plotted at the same vertical scale as for the aligning moment. The overturning moment appears relatively insensitive to speed, except in the

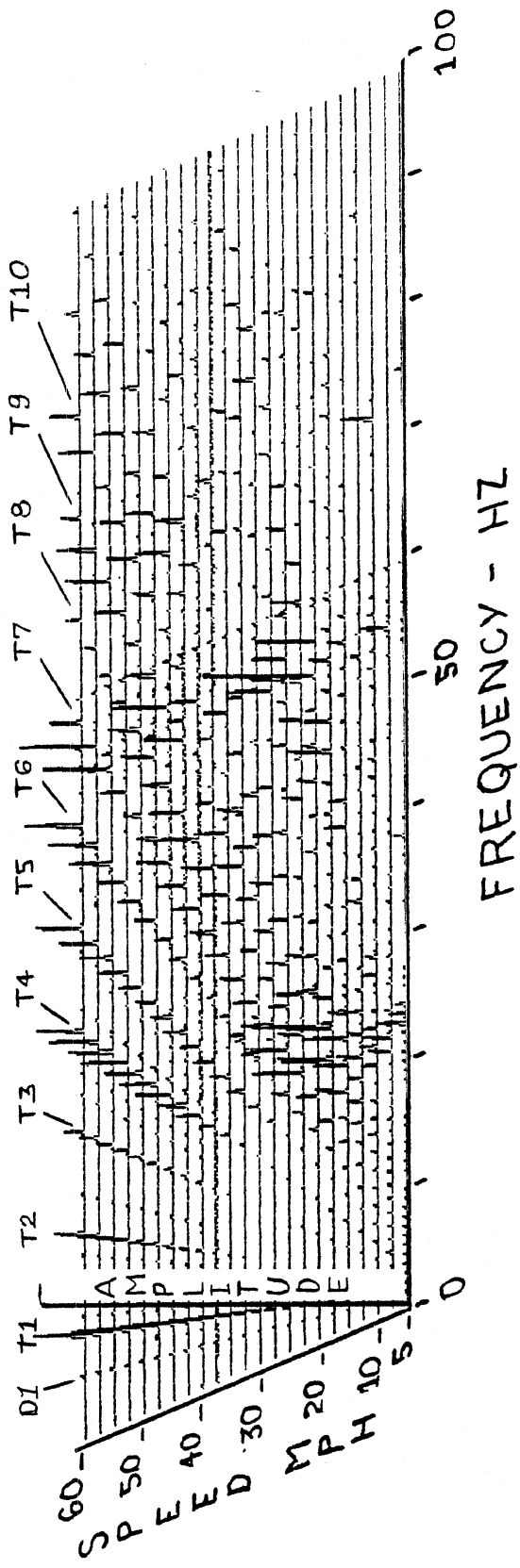


Figure 8. Spectral map of tractive forces.

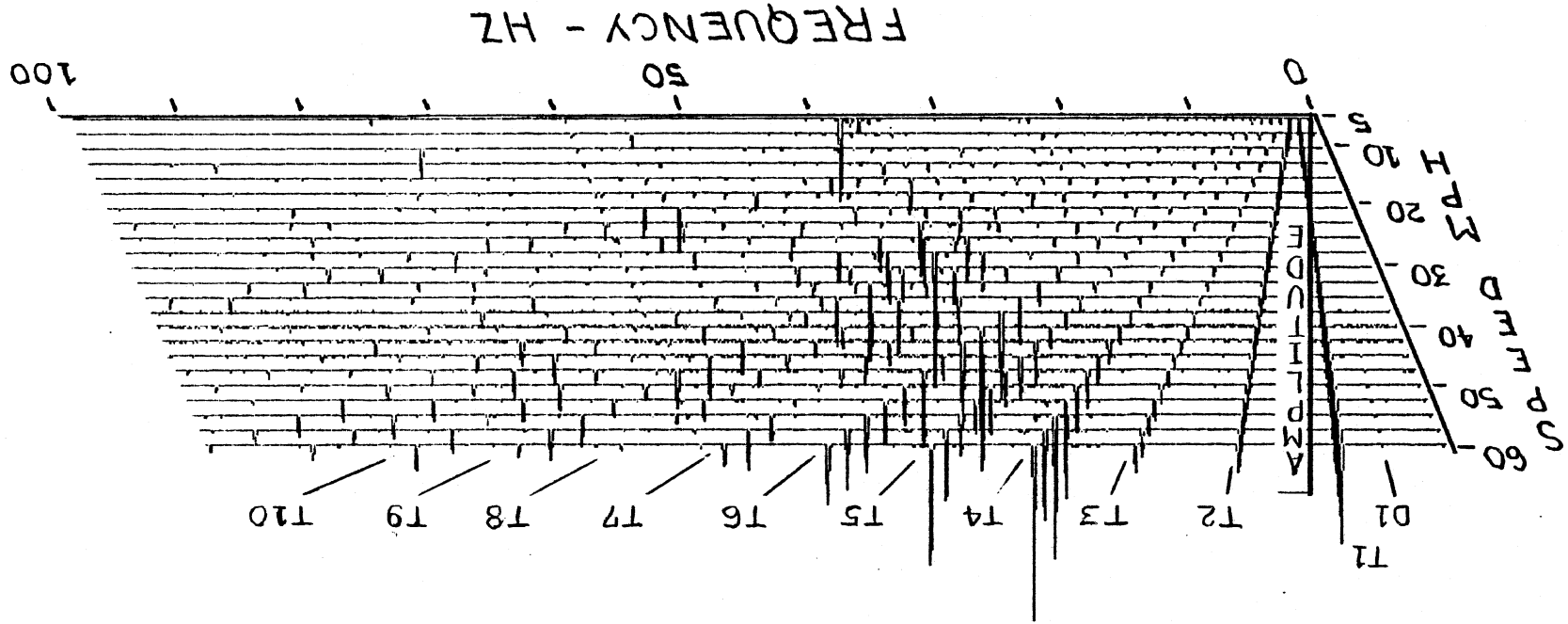


Figure 9. Spectral map of aligning torque.

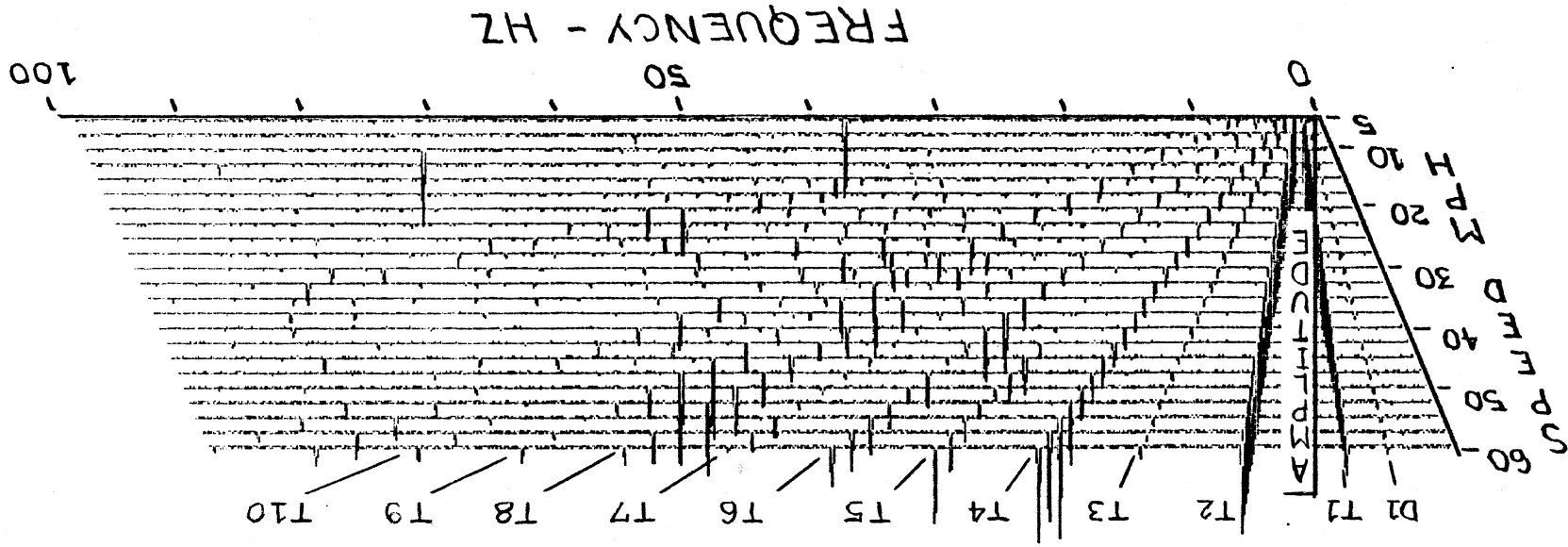


Figure 10. Spectral map of overturning moment.

frequency range of 28 to 42 Hz, and in the 50 to 60 Hz range. The moment amplification that occurs in these frequency ranges matches that of the aligning moment, and is likely to be the consequence of the resonances discussed previously. Based on this map *it is concluded that the UMTRI machine measures overturning moment variations validly over the frequency range from 0 to 25 Hz. Its validity in the range of 25 to 100 Hz has yet to be proven when the resonances have been identified.*

Rolling Resistance Moment (My) - The rolling resistance moment is measured by the UMTRI tire test machine, but is of such a low magnitude that the moments tend to be masked by noise in the data acquisition system.

Summary and Conclusions

This brief report has attempted to present an overview of the UMTRI Tire/Wheel Uniformity Test Machine, and the performance capabilities it offers. Although only given limited testing it appears capable of valid measurements of radial, lateral, and tractive force variations, and aligning and overturning moment variations over a frequency range that goes beyond that of the previous MTS tire test machine. From the limited analysis to date, only one low-frequency machine resonance problem has been identified—a 31 Hz lateral resonance on the laboratory floor. Tire resonances are also evident near this frequency. The machine resonance interferes with valid measurements of lateral force, aligning torque, and overturning moment near its frequency but has no effect on radial and tractive force measurements.

In its current state, the machine provides valid measurements in the radial and tractive force directions over the frequency range from 0 to 50 Hz. For lateral force, aligning torque, and overturning moment the machine is valid from 0 to 25 Hz. With additional structure to provide lateral support, its capability in these directions can probably be increased to 50 Hz.

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