A Novel Measure Method for High-Speed Tire Vibrations

GUSTAVO A. SCHWARTZ
FATE SAICI, Department of Research and Development, Av. Blanco Encalada 3003, San Fernando, Prov. de Buenos Aires (1644), Argentina

(Received 2 February 1999; accepted 3 October 2000)

Abstract: With the arrival of faster cars, it was necessary to make a considerable improvement on tire performance. At high speed, tire nonuniformities begin to induce vibrations that are perceived by the passengers and finally degrade vehicle ride quality. Nowadays, it is not possible to guarantee through the usual methods uniformity values (longitudinal, radial and lateral force variations, wheel and tire run out), X-ray inspection, and so on, that a given tire will have a good behavior at high speed. This paper presents a new methodology that makes possible the correlation of high-speed tire vibrations with the measured behavior on an instrumented drum wheel (IDW) at a laboratory. Several tires of different sizes and brand names were measured, and the values were compared with subjective evaluations made on different vehicles. The obtained data were analyzed as a generalization of the model proposed by Walker and Reeves in 1974.

Key Words: Tire vibrations, nonuniformities, random vibrations, harmonic analysis

1. INTRODUCTION

Periodic sound and vibrations of vehicles are usually detectable on smooth road surfaces at relative high speeds, above 100 km/h. These periodic vibrations represent a recurring pattern of vibrations or force variations. They may originate in nonuniform conditions of many of the rotating components or elements of the vehicle, such as the engine, driveline, brake rotors, engine accessories, and tire-wheel assemblies, as examples. Tire nonuniformities contribute to these vibrations and are caused by structural, geometric, and material irregularities of the tire, typically arising due to vagaries of manufacture, resulting in a variety of symptomatic and causal conditions, including, but not limited to, force and geometric variations, axial asymmetry of tread, and so on (Oblizajek, 1995).

Some nonuniformities, such as radial or lateral force variation, wheel and tire run out, conicity, and so on, are detected when tested on uniformity machines. Other nonuniformities, such as defective belt splices, off-center belts, or snaked belts, can be detected through X-ray inspection or holographic interferometer.

The usual tire uniformity machines are able to measure radial and lateral force variations (RFV and LatFV) at low speed, about 17 km/h (1 Hz). These variations do not depend essentially on velocity (Walker and Reeves, 1974). The most important speed dependence appears in the longitudinal force variation (LFV) (Walker and Reeves, 1974). These variations will

Journal of Vibration and Control, 7: 643-651, 2001

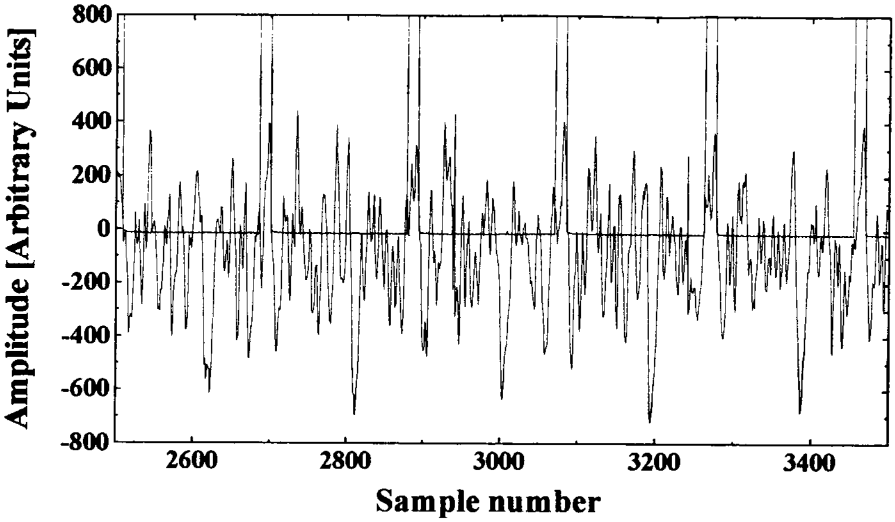

Figure 1. Tire vibration signal for five revolutions of the wheel. Each vertical pulse indicates the beginning of a new revolution.

have an average value related to the rolling resistance force, and they are partly related to the radial run out (RRO) and to the radial force variations (RFV). It is well-known that the steering wheel vibrations are strongly correlated with the LFV (70%) and for a minor part (30%) to RFV (Clark, 1981, p. 625).

A considerable effort has been made for years, by the tire manufacturers, to lower uniformity values. Many researchers have tried to correlate uniformity values (RFV, RRO, etc.) with the vehicle ride quality. The work of Holcombe and Altman (1988) relates the maximum RFV, static balance, RRO, and others uniformity parameters with subjective tests on vehicles. But they did not include the LFV in their analysis. A more recent work (Oblizajek, 1995) relates high-speed force variations with low-speed ones. This method allows tire manufacturers to predict the behavior of the roadway typical forces from special measurements and combinations thereof obtained at low speeds. Finally, the present work relates high-speed measurements of LFV with vehicle ride quality. I describe here the implementation details of this methodology and analyze some applications to select and improve car tires.

2. BACKGROUND

2.1. Stationary Random Vibrations

Random vibrations are met rather frequently in nature and may be characterized as vibratory processes in which the vibrating system undergoes irregular motion cycles that never repeat themselves exactly. Figure 1 shows tire vibration signals for five revolutions of the wheel. It may be seen that its statistical characteristics, such as mean value, root mean square value,

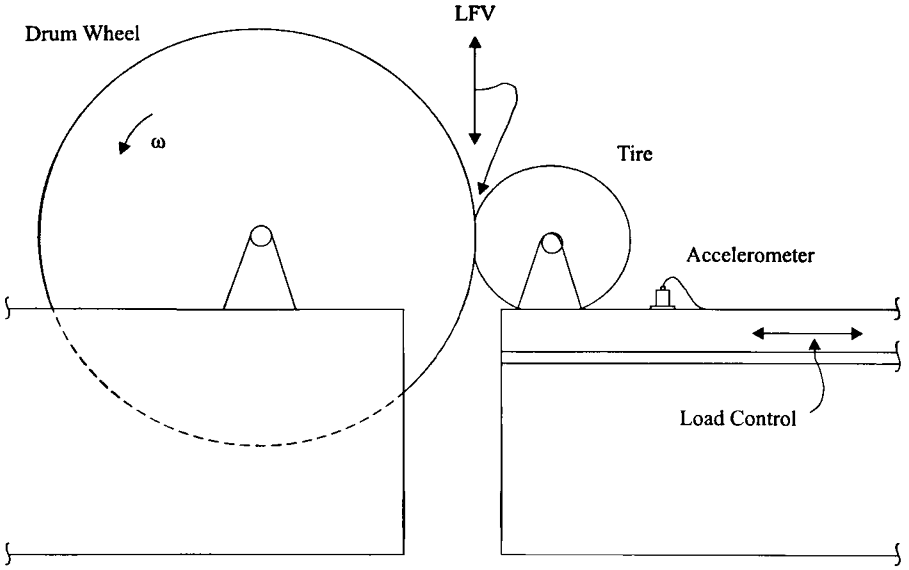

Figure 2. Sketch of the experimental arrangement.

variance, and so on, do not change with time. The vibrations characterized by this type of signal are called *stationary random vibrations* (Broch, 1984).

The whole signal is the result of a repetitive pattern plus random noise. We are interested in extracting the periodic part of the signal. To do this, we can average many periods to reduce the noise considerably. This is possible only if we can know exactly where each period starts. In this case, it is possible to average signals, and this methodology is known as *synchronous averaging*.

Synchronous averaging is an averaging of digitized time records, the start of which is defined by a repetitive trigger signal. One example of such a trigger signal is a once-per-revolution synchronizing pulse from a rotating shaft. This process is useful in enhancing the repetitive part of the signal (whose period coincides with that of the trigger signal) with respect to nonsynchronous effects. That part of the signal that repeats each time adds directly in proportion to the number of averages, n. The nonsynchronous components, both random noise and periodic signals with a different period, add like noise, with random phase; the amplitude increases in proportion to $n^{1/2}$. The overall improvement in the signal-to-noise ratio is thus $n^{1/2}$, resulting in an improvement of, for example, 10 dB for 10 averages (Harris, 1988, pp. 13-42).

3. EXPERIMENTAL PROCEDURE

Figure 2 shows a sketch of the experimental arrangement. This equipment enables analysis of the tire behavior in a wide range of conditions, not only at low but also high speed (until 240 km/h). The tire is mounted on a precision rim and is loaded against a drum that can rotate at controlled speed.

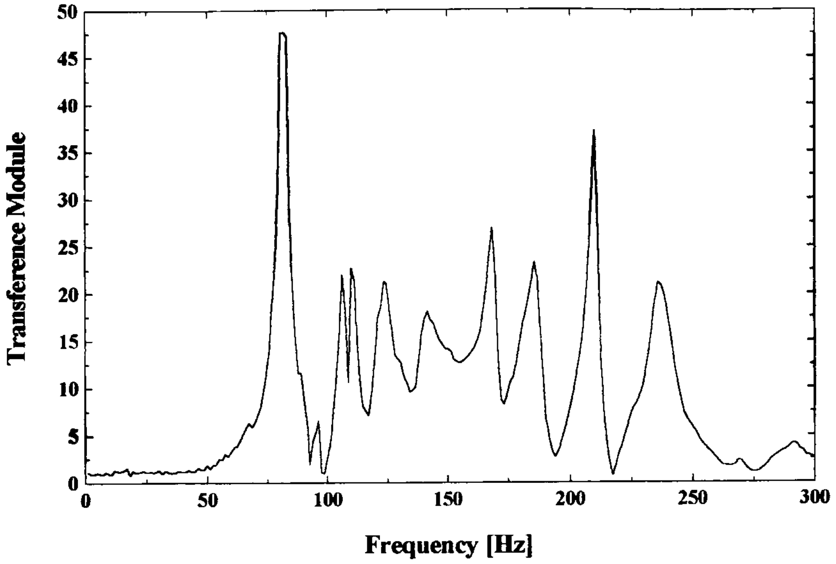

Figure 3. Frequency response of the mechanical system.

The contact longitudinal force between the tire and drum, at constant velocity, may be written as

$$F_{tang} = F_{RR} + F_{Re} + LFV + \varepsilon \,, \tag{1}$$

where F_{RR} is the rolling resistance force, F_{Re} is the resistance force at the axis, LFV is the longitudinal force variation, and ε is Gaussian noise. At a given speed, it can be considered that F_{RR} and F_{Re} are constant, while the last two terms will change in time. These variations are reflected in the axis and support of the tire in form of mechanical vibrations that can be detected and measured; from this measure, it is possible to estimate the LFV.

4. FREQUENCY RESPONSE OF THE MECHANICAL SYSTEM

The frequency response of the mechanical system was measured by stimulating it with an instrumented hammer (Bruel & Kjaer 8202) and measuring the response with a piezoelectric accelerometer (Bruel & Kjaer 4281). From the fast Fourier transform (FFT) (Oppenheim and Schafer, 1975; Brigham, 1988) of both signals, it is possible to obtain the transference function of the system as

$$\mathbf{T} = \mathbf{FFT}[\text{resp}]/\mathbf{FFT}[\text{exc}] \,. \tag{2}$$

Figure 3 shows a typical frequency response function. A flat response can be seen until 50 Hz, followed by an important peak centered at 80 Hz. It is desirable to obtain a flat response at least in the range of 0 to 300 Hz that corresponds to the first 10 harmonics for speeds

Table 1. Uniformity parameters of the selected tires.

	Set 1				Set 2				Set 3				Set 4			
Param	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
RFV	8.4	9.6	9.7	8.4	8.7	14	9.5	11.8	9.6	15.1	10.8	8.1	14.2	9.7	12.3	8.4
RFV1	1.9	6	5.6	2.1	2.4	6.7	3.7	6.1	5.1	9.6	2.5	4.1	3	4.8	5.1	3.9
RRO	20.6	23.6	25.3	29.9	25.3	30.8	20	23.3	29.2	35.2	19.5	23	27.2	21.5	27.8	21.4

NOTE: RFV1 is the first harmonic of radial force variations (RFV). RFV and RFV1 are in pounds; radial run out (RRO) is in 10^{-3} inches.

of up to 200 km/h (depending on tire size). However, even with the obtained response, it is possible to "reconstruct" the measured signal in the following way:

$$\mathrm{S[real]} = \mathbf{FFT}^{-1}[\mathbf{FFT}[\mathrm{S[measured]}]/\mathrm{T}]\,, \tag{3}$$

where S[measured] is the signal registered by the accelerometer and S[real] is the corresponding observed physical quantity. Although this response is similar for different tires with the same construction, the response was measured for each tire.

It is also possible, without any type of transformation, to make a comparative analysis when tires with the same characteristics are tested; see Different Construction Effects section, in Results and Discussion for more details.

5. EQUIPMENT

Mechanical vibrations were measured with a piezoelectric accelerometer (Bruel & Kjaer Type 4281) and a charge amplifier (Bruel & Kjaer Type 3584). Data were captured in a personal computer through a data acquisition system. A proximity sensor was set to detect a once-per-revolution synchronizing pulse from a rotating shaft where the tires were mounted. The signals were obtained and processed by a program developed in Lab/Windows CVI of National Instruments.

6. TIRE CHARACTERIZATION AND PREPARATION

All selected tires were measured on a uniformity machine, and the uniformity parameters (RFV, RRO, etc.) were obtained. Table 1 shows these values for all tires. Then the tires were mounted with a tube on a precision rim. Load and inflation pressure were the corresponding ones for passenger cars in SAE J332 norm. Before each test, the tire was run at 100 km/h for about 15 minutes to raise temperature and to reach a stationary rate.

7. RESULTS AND DISCUSSION

7.1. *Harmonic Analysis*

The first harmonic of the LFV presents a strong increase according to speed that allows one to suppose the following dependence on speed for the LFV:

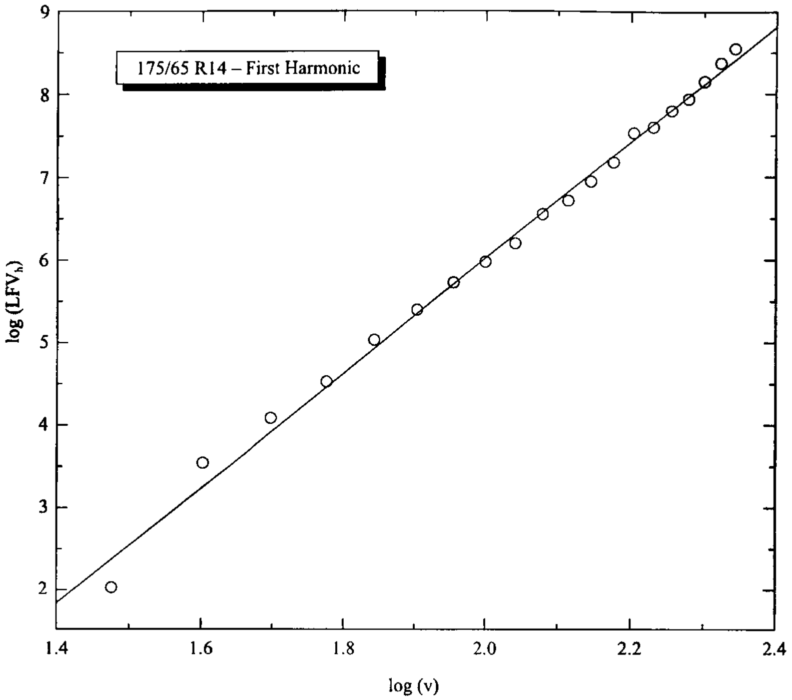

Figure 4. Experimental data (open circles) fitted with equation (5) (line). Note the wide range for speed (from 30 to 210 km/h).

$$LFV_h = av^{b}, \tag{4}$$

where a and b do not depend on speed and LFV_h represents LFV first harmonic. Taking logarithms in both members, we obtain the following:

$$\log(LFV_h) = \log a + b \log v \ . \tag{5}$$

Figure 4 shows the agreement of the experimental data with equation (5) for the LFV first harmonic of a 175/65 R14. A particular case of this model was proposed by Walker and Reeves (1974) with $a = I(\Delta R/\bar{R}^3 R_h)$ and $b = 2$, where I is the moment of inertia of the wheel and tire, ΔR the radial run out, R the average rolling radius, and R_h the axle height.

It is interesting to note that for different tires, a and b do not have the same values; moreover, a and b are not independent. Figure 5 shows the relation between a and b for more than 30 tires of different sizes and trademarks.

This fact leads to a family of curves of the following type:

$$f(v, a) = av^{(\gamma + \delta a)}, \tag{6}$$

where v is the speed, and γ and δ are constants.

Consequently, it is impossible to diminish a and b at the same time; it is necessary to find a balance that enables improvement of the tire performance.

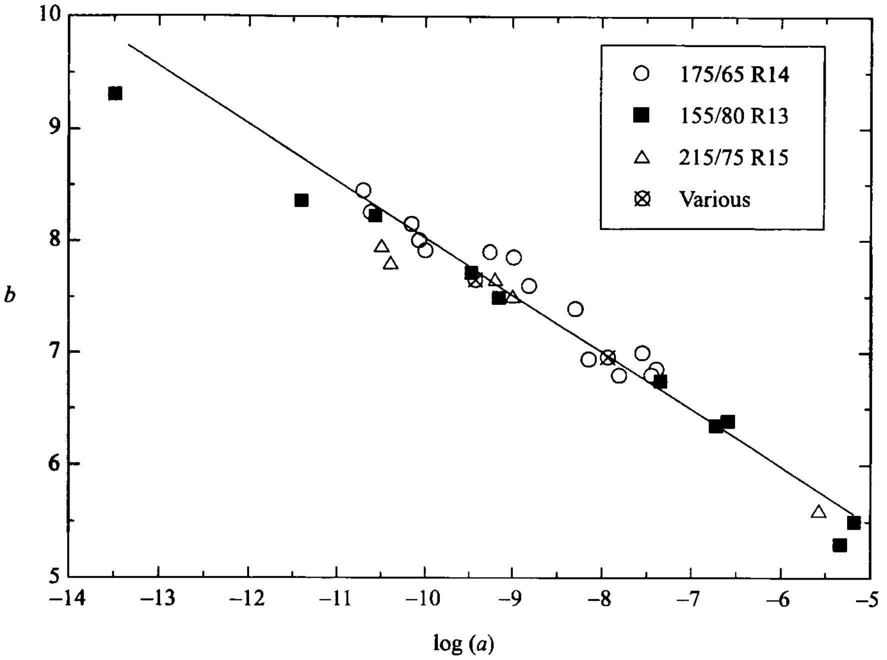

Figure 5. Relation between a and b for more than 30 tires of different sizes and trademarks.

Table 2. Effect of rubber thickness on the fifth harmonic of the longitudinal force variation (LFV).

	Speed[km/h]					
Thickness	110	120	130	140	150	160
1.17 mm	5.84	6.07	6.24	6.06	5.97	6.03
1.50 mm	6.43	6.71	6.69	6.54	6.3	6.47

NOTE: The values represent log(fifth harmonic LFV) in arbitrary units.

7.2. Different Construction Effects

It is possible to associate some harmonics with constructive parameters. For example, the steel belt has five unions along the tire circumference. Thus, the problems associated with these unions may be reflected in the fifth harmonic. This allows evaluation of the effect of increasing the rubber thickness of the steel belt. Tires with two different steel belt rubber thicknesses were constructed, and this methodology was used to measure tire vibrations. Results are shown in Table 2.

It can be seen in Table 2 that tires with greater rubber thickness have higher values on the fifth harmonic of the LFV; the average differences are greater than half an order of magnitude, indicating how the steel belt with greater thickness shows the union effects.

Table 3. Comparison between instrumented drum wheel (IDW) and subjective methods for four sets at different speeds.

Set	Method	Speed [km/h] 110	120	130	140	150	160	Mean	Ranking
Set 1	IDW	1125	1075	950	1000	1225	2025	1233.33	
	Subjective	10	10	10	10	10	9.5	9.92	1
Set 3	IDW	2175	2625	2750	2225	2525	3450	2625.00	
	Subjective	10	10	10	9.5	9.5	9.5	9.75	2
Set 4	IDW	2375	3350	3050	2775	3075	4175	3133.33	
	Subjective	10	10	9.5	9.5	9.5	9.5	9.67	3
Set 2	IDW	2125	2400	2300	3175	3500	5625	3187.50	
	Subjective	10	10	9.5	9	9.5	9.5	9.58	4

NOTE: Comparison between the results obtained by this methodology and the subjective test. The laboratory-measured values are in arbitrary units, and those corresponding to subjective test are from zero for the worst to 10 for the best.

7.3. Correlation With Subjective Test

Sixteen tires were tested (four sets of four tires each) at velocities in the range of 110 to 160 km/h. Tire load and pressure are those specified in the norm SAE J332 for passenger cars. The data obtained were processed as mentioned before, and the results are shown in Table 3. For each set, the mean of the four tires and finally the mean of the mean at each speed were calculated, obtaining in this way a number that represents the global behavior of the set at the different speeds. It is clear that a lower value indicates better performance.

Table 3 shows the comparison between the values obtained by this methodology and the subjective ones made by test drivers. The subjective evaluation was based on steering wheel, seat, and floor vibrations. The laboratory-measured values are in arbitrary units, and those corresponding to subjective tests are from zero for the worst to 10 for the best.

Although Table 3 shows good agreement between laboratory and subjective tests, the fit is not exact. The differences may be attributed to the way in which the tires are located in the vehicle; if the front tires have values above (or below) the mean, steering wheel vibrations may be higher (or lower). Other error sources are the irregularities of the road and other random factors.

Despite these differences, the mean of the means at each speed shows good agreement with subjective results; this enables us to predict tire behavior at high speeds from a laboratory test.

8. CONCLUSIONS

A novel indoor methodology to measure tire vibrations at high speed was presented. The results show good agreement with subjective tests in vehicles. This methodology enables us also to evaluate experimental tires, to test sampling tires from production, to test variations, and so on.

An empirical generalization of the Walker and Reeves model was proposed.

It could be interesting to include the longitudinal force variation in the analysis made by Holcombe and Altman (1988). This should improve the method considerably because the longitudinal force has strong speed dependence while RFV and RRO do not. Also, it is possible to use this methodology, combined with the method developed by Oblizajek (1995), to select original equipment tires by means of the existing end-of-line inspection equipment.

Tire noise data show a similar dependence on velocity for each third-octave band. These data have been analyzed, and results will be published in a future work.

Acknowledgments. The author wishes to thank FATE SAICI for allowing the publication of it.

REFERENCES

Brigham, E. O., 1988, *The Fast Fourier Transform and Its Applications*, Prentice Hall, Englewood Cliffs, NJ.

Broch, J. T., 1984, *Mechanical Vibration and Shock Measurements*, Bruel & Kjaer, Denmark.

Clark, S. K., 1981, *Mechanics of Pneumatic Tires*, National Highway Traffic Safety Administration, Washington, DC.

Harris, C. M., 1988, *Shock & Vibration Handbook*, McGraw-Hill, New York.

Holcombe, M. G. and Altman, R. G., 1988, "A method for determining tire and wheel uniformity needs using ride rating simulations," Paper 880579, Society of Automotive Engineers, Warrendale, PA.

Oblizajek, K., 1995, US Patent No. 5396438.

Oppenheim, A. V. and Schafer, R. W., 1975, *Digital Signal Processing*, Prentice Hall, Englewood Cliffs, NJ.

Walker, J. C. and Reeves, N. H., 1974, "Uniformity of tires at vehicle operating speeds," *Tire Science and Technology* **2**(3), 163-178.