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Physical Modeling of a Dynamic Dial Indicator for the Non-Destructive Evaluation of Tire Tread Viscoelastic Characteristics

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Abstract— **The evaluation of the tire tread viscoelastic characteristics, especially by means of non-destructive procedures, is a particularly interesting topic for motorsport teams and companies, used to work with unknown and confidential compounds. The availability of such information would define new scenarios in vehicle analysis field, as the possibility to provide physical inputs to tire grip models or the study of the suspensions setup able to make tires work inside their optimal thermal working range.**

The employment of commercial devices allows to select by means of specific indices the optimal combination of tires to be installed on a vehicle, but it does not provide any information physically correlated with the tread polymers characteristics. The aim of the presented activity is the modelling of one of the cited devices, a dynamic dial indicator, interacting with a viscoelastic half-space. The obtained results allow, analyzing the signals acquired by the device, to identify the tread equivalent stiffness and damping as a function of tire working temperature, providing the basic guidelines for the development of an innovative procedure for a full non-destructive viscoelastic characterization of the tire compounds.

Index Terms—**Material non-destructive characterization, temperature effect, tire tread compound behavior, TSD, viscoelastic characteristics.**

I. Introduction

The characterization of tire tread viscoelasticity is a fundamental topic in a wide range of activities concerning the development of polymers for innovative compounds, the parameterization of physical contact models and the optimization of vehicle performance and road safety, also as concerns bicycle behavior [1].

Regarding the cited branches, one of the main aims of the tire production industry is focused on the research of materials mixtures able to guarantee maximum frictional performances and low energy dissipations for the longest time possible; in order to achieve such goal, the knowledge of the tread polymers characteristics is a key factor. Common testing procedures involve complex and expensive benches [2][3][4] requesting the analysis of single rubber specimens especially produced or obtained from the tire, thus the tire has irremediably to be destroyed.

As concerns the identification of the parameters of contact and friction physical models [5][6], the availability of data on the thermal and structural behavior of the tread compounds provides an increase in the reliability and the predictivity of the proposed formulations, often parameterized in “reverse” basing on tribological experimental data [7][8]. The possibility, moreover, to obtain such parameters by means of a non-destructive methodology would allow to preserve tire integrity and to exclude the boundary effects linked to the testing of small specimens.

Motorsport racing teams use to face with the restrictions linked to the employment of confidential tires, provided by tiremakers and not available to invasive testing. The development of procedures for the acquisition of data concerning the tire thermal working conditions represents an innovation able to make the difference in the definition of the optimal vehicle setup and of the realization of strategic vehicle simulation tools [9][10][11].

Finally, a real-time compounds characterization, performed by means of a portable device, allows to study the direct effects due to tread wear [12][13], to tire heating and cooling [14] and to winter and summer season compounds selection [15] on track and road dynamics, aimed to the improvement of safety (braking distance reduction) and handling (laptime reduction) vehicle performances.

The current paper describes a physical model of a dynamic dial indicator, developed with the commercial aim to provide some distinction criteria among tires by means of particular indices based on the analysis of the acquired signal. The target of the authors is to employ such device with an innovative approach, focused on the evaluation of the tread viscoelastic characteristics. At the current stage of the activity the dynamical model is described and its first results are presented and compared to the experimental ones. The final target is the identification of the stiffness and damping parameters of the tested body, with the clarification that the procedure is general and applicable to any kind of material and surface.

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II. TSD (Tyre Selection Device)

The TSD is a device by Dufournier, usable outdoor and even on track, for non-destructive testing, control and qualification of tires, aimed to obtain information also on the compounds.

Its main components are:

- a spring return displacement transducer with a preload, as shown in Fig. 1;

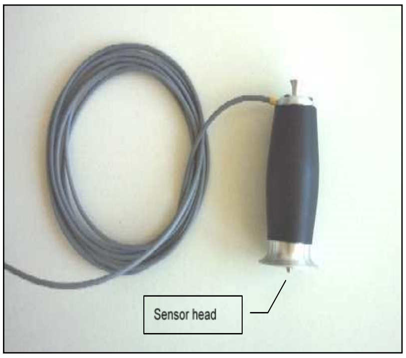

Fig. 1. TSD transducer.

- a data acquisition unit (Fig. 2)

Fig. 2. TSD data acquisition unit.

- a software for data reading and processing.

This device is able to classify any type of tire and its characterization is based on two criteria:

– The module criterion (Cm) which qualifies the module of the tire tread, compared to the average module of the set or of the individual reference tire;
– The loss coefficient criterion (Cp) which qualifies the tread loss ratio compared to the average loss coefficient of the set or of the individual reference tire.

The TSD manufacturer suggests the calculation procedure for the two parameters used in the characterization criteria (Figure 3): the Cm is calculated as the difference between the ordinate of the curve minimum point, representative of the sensor-compound contact, and the one in which the signal stabilizes; the Cp is calculated, always starting from the point of minimum of the curve, but comparing it with the ordinate of the point of maximum rise of the curve.

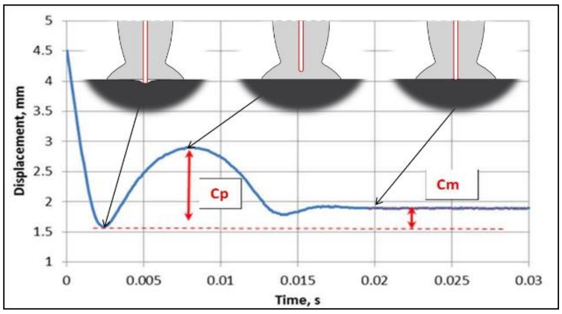

Fig. 3. TSD output curve and Cm and Cp definition.

Summary of the previous two criteria is the dispersion criterion, used by the device as a last characterization, whose equation is:

$$Cu = \sqrt{Cp^2 + Cm^2} \tag{1}$$

Using the integrated development environment LabVIEW a self made customized code for the data acquisition from the sensor has been developed, since the software provided by the TSD manufacturer did not allow to get in output the acquired data time histories.

This customized software is based on the use of a chain composed by three consequential trigger:

- the first is activated when the rod is above a certain quota rising;
- the second is turned on when the sensor rod is at the highest point of its stroke ready to be released;
- the third, which indicates the acquisition starting point, prompts at a specific value of the rod descent stroke. The software acquires with a sample interval of 10^{-4} seconds, properly set in the design phase, acquiring 1000 samples per measurement.

Therefore, to properly execute the test it is necessary to adopt the following procedure:

1. The sensor head is positioned on the tire surface in correspondence of the precise zone under analysis;
2. The rod is raised inside the sensor gauge till the highest point of its stroke is reached (Figure 4);

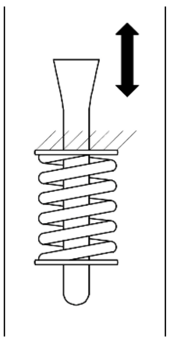

Fig. 4. TSD Mechanical scheme of the TSD transducer.

3. The rod is totally released;
4. The raw data are acquired, displayed to find out any acquisition anomalies, and then processed.

The typical TSD output is shown in Figure 2. It is possible to recognize the three test characteristic steps:

- the first stage is characterized by the impact of the sensor rod on the tire surface and it corresponds to the minimum point of the rod displacement curve;
- during the second phase, the rod bounces to the maximum point of the curve because of its interaction with the external tire rubber layer;
- the third step is characterized by a stabilized rod height value established within the contact of the sensor and the tire coating at the end of the transient reciprocal dynamics.

The acquired curve can be used to obtain the *Cp* and *Cm* values above described and to determine the material mechanical properties.

III. Experimental Results

The first experimental tests, shown in the following, have been conducted on a high performance GT tire at different external tread temperatures. The tire was inflated at the nominal internal pressure of 1.85 bar.

Each test has been repeated at least ten times at the same tire point, approximately at the tread center zone, to neglect the structure response influence.

To highlight the variation of the compound behavior at different temperature values, the experimental campaign has been conducted within a range of 25°C÷135°C.

Figure 5 shows a comparison of different material behaviors at different temperatures by means of the TSD device output curves.

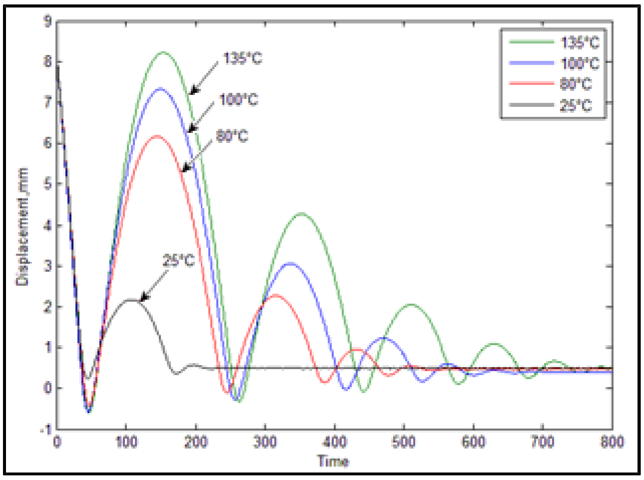

Fig. 5. TSD output characteristic curves evidencing the tire compound response at specific temperature values.

It is evident that the number of the TSD rod rebounds and the first rebound maximum height value, immediately after the impact, are increasing with temperature. So, the polymeric material in analysis exhibits an increase of the stiffness and a decrease of the damping equivalent modules with a temperature increment.

IV. Characterization and Dynamical Modelling of the Device: Two Lumped Mass Model

The TSD gauge and the material to be tested are schematically modelled as a two-lumped mass system (Fig. 5). The first mass m_1 is associated with the device movable part (TSD rod), while the mass m_2 is associated with the portion of the tested material interested by the rod impact.

The mass m_1 is concentrated at the rod physical head, while the mass m_2 is positioned on the tire compound surface. The reference system origin is located in correspondence of the contact point of the rod with non-deformed material, so that the unique reference axis z coincides with the rod axis of symmetry and points up.

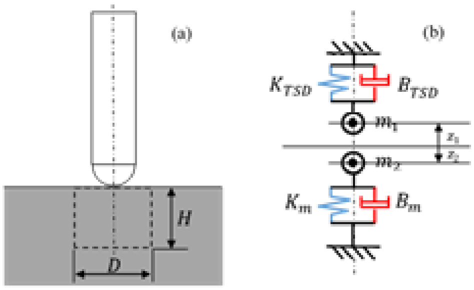

Fig. 6. Scheme of the TSD device in contact with the material (a) and of the two-lumped mass dynamical model (b).

The TSD device is modeled as a preloaded mass-spring-damper system, whose stiffness and damping parameters are respectively indicated with K_{TSD} and B_{TSD}, while the preload acting on the mass m_1 is indicated with F_0.

The tested material (tire tread compound) affected by the impact is confined, by assumption, in a cylindrical volume of diameter D and depth H coaxial with the axis of the rod (Fig. 5), so that, given the density ρ, the m_2 mass can be expressed as:

$$m_2 = \rho\left(\frac{\pi D^2}{4}\right)H \quad (2)$$

It has been modeled as a mass-spring-damper system (without preload), whose stiffness and damping parameters have been respectively indicated with K_m and B_m.

The mass m_1 instead coincides with the rod one.

Therefore, the masses move along a common direction, defined by the axis of the rod and their motion is governed by the following expressions:

$$\begin{aligned} F_c + F_{K,TSD} + F_{B,TSD} + F_0 &= m_1 a_1 \\ -F_c + F_{K,m} + F_{B,m} &= m_2 a_2 \end{aligned} \quad (3)$$

if the rod is in contact with the tire tread, and:

$$\begin{aligned} F_{K,TSD} + F_{B,TSD} + F_0 &= m_1 a_1 \\ F_{K,m} + F_{B,m} &= m_2 a_2 \end{aligned} \quad (4)$$

if the rod is not in contact with the tire tread.

Where:

$F_{K,TSD}$ is the elastic force associated to the TSD spring (K_{TSD}) for the return of the displacement transducer (rod);

$F_{B,TSD}$ is the viscous force (B_{TSD}) associated to the rod motion proportional to its velocity;

F_0 is the TSD spring preload;

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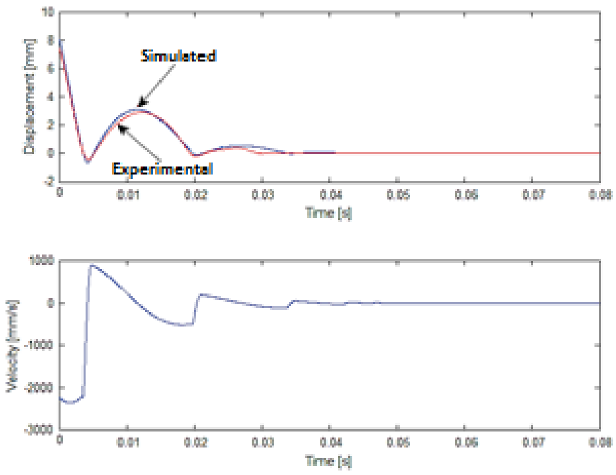

Fig. 7 TSD rod experimental displacement in a test on the tire surface compound at a temperature of 35°C (red) vs TSD rod simulated displacement (blue) (above) TSD rod simulated velocity (below).

$F_{K,m}$ is the elastic force associated to the tested material stiffness (K_m);
$F_{B,m}$ is the viscous force associated to the tested material damping (B_m);
a_1 and $a2$ are respectively mass $m1$ and mass m2 linear accelerations;
Fc is the contact force between the two masses;

The contact between the two masses is modelled by means of a contact stiffness (K_C), which acts generating a contact force F_C (considered with the + o – sign if, respectively, referred to m_1 or m_2) only if the penetration condition z_2>z_1 occurs.

The mutual contact force F_C can be expressed as:

$$F_c = \pm \begin{cases} 0 & if\ z_1 \geq z_2 \\ K_c|z_1 - z_2| & if\ z_1 < z_2 \end{cases} \qquad (5)$$

In order to optimize the computational burden it has been ometted the use of conditions inside the code.

V. Results and Discussion

In the diagram above of figure 6, as an example of material properties identification, the curve representing the time history of TSD rod displacement of an experimental test conducted on the tire surface compound at a temperature of 35°C is reported together with the same curve coming out from a simulation conducted using the parameters of TAB. I, and the following initial conditions z_1=+8 mm, z_2=0, $\dot{z}_1$= = 0 m/s, $\dot{z}_2$=0 m/s.

TABLE I
Parameters of the Two Mass Model

Symbol	Quantity	Value
m_1	mass	35*10^{-3} kg
K_{TSD}	stiffness	1.5 *10^3 N/m
B_{TSD}	damping	3 N s/m
m_2	mass	2,3*10^{-3} kg
K_m	stiffness	1.6*10^5 N/m
B_m	damping	47,1 N s/m
D	length	3*10^{-3} m
H	length	3*10^{-3} m
ρ	density	1100 Kg/m^{-3}

The diagram below in figure 7 shows the simulated velocity of the TSD rod.

As it is possible to see in the figure the two results (experimental and simulated) are in good agreement.

It is necessary to highlight that device parameters reported in table I have been measured, while tested material parameters reported in the same table have been identified to fit the experimental curve with the lumped mass model results.

This means that it is possible to estimate material elastic modulus and viscosity starting from lumped mass system parameters.

In particular, in the specific case study it is possible to find out that at the temperature of 35°C the rubber compound of the considered high performance GT tire exhibits an elastic modulus E equal to 7*10^7 N/m^2 and a viscosity η equal to 2*10^5 Pa*s.

Clearly this is only a single application of the procedure, repeating this procedure for different temperatures it is possible to identify how material properties change as a function of temperature.

It is also important to point up that this procedure is general and applicable to all kinds of materials.

VI. Conclusion

In this paper a procedure useful to characterize superficial mechanical properties of materials in a non-destructive way has been presented. This procedure is based on the use of a commercial dial indicator, TSD, equipped with a customized acquisition code and on the use of a two-lumped mass system modelling the dynamical behavior of the TSD and of the tested material.

The procedure idea is to compare experimental TSD results with the model simulation to identify tested material mechanical properties.

After the description of the device, of the experimental setup and of the two degrees of freedom model a case study has been discussed, presenting the entire procedure.

The particular case study presented has the aim to estimate in a non-destructive way tread equivalent stiffness and damping of a high performance GT.

The obtained results are in good agreement both with mechanical properties data available in literature and with physical expetations.

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