Investigation of the Mileage Effects on the Viscoelastic Properties by a Non-destructive Method

Francesco Timpone, Gianpaolo Contrada, Michele Sanfelice, Vincenzo Arricale(✉), and Guido Napolitano Dell'Annunziata

University of Naples Federico II, Naples, Italy
{timpone,gi.contrada,michele.sanfelice,vincenzomaria.arricale, guido.napolitanodellannunziata}@unina.it

Abstract. The viscoelastic properties of tires play a fundamental role into vehicle dynamics field affecting the vehicle performance and safety according to their evolution over the mileage. The knowledge of these properties is obtained through destructive tests, such as the Dynamic Material Analysis, which make the tire unusable. In this scenario, the Applied Mechanics research group of the Department of Industrial Engineering at the Federico II has developed an innovative device, called VESevo, capable of providing a smart and non-destructive characterization of the viscoelastic properties of tires tread compound. This new device allows to characterize tires obtained important information about the evolution of viscoelastic properties of a same tire over its mileage, opening scenarios of interest in a very broad panorama of applications ranging from the monitoring of the material performance during its whole lifecycle, to the quantitative analysis of products quality and repeatability of production processes. In this work, the authors show how the viscoelastic properties of a tire change as function of its mileage.

Keywords: Viscoelasticity · Tire · Polymer · Non-destructive test

1 Introduction

In the vehicle dynamics, the knowledge of the viscoelastic properties of the tire tread is a key factor to understand the phenomena occurring in the interface between tire and road. Indeed, the knowledge of such properties allows to improve and optimize the vehicle stability, performance and safety [1, 2].

In the last decades, many theories and models about the interaction tire-road have been developed and discussed [3–7], but the analysis of the contact problem requires full experimentally-based knowledge of the roughness profile and the rubber viscoelastic properties. To make the problem even more complex the tire properties are not steady and vary according to its conditions: new or worn. The most common way to characterize the materials' viscoelastic behaviour is the Dynamic Mechanical Analysis (D.M.A.), which also allow to define the hysteretic behaviour of the compound following the

V. Niola et al. (Eds.): IFToMM Italy 2022, MMS 122, pp. 430–438, 2022.
https://doi.org/10.1007/978-3-031-10776-4_50

time-temperature superstition principle [8]. If on the one hand this technique provides with information about viscoelastic properties, on the other hand, it requires expensive equipment and to damage the tire, making it unusable. Moreover, in most application, as well as motorsport ones, the tires are linked to restrictions, and they cannot be analysed by the standard procedures. In this scenario, the possibility to obtain the compounds viscoelastic response by mean of a totally non-destructive and non-invasive procedure is a key factor for several applications, from the development of polymers for innovative compounds to vehicle performance and safety, gaining the attention of industries and academics from different sectors [9–13].

In this work, an innovative device, named VESevo (Viscoelasticity Evaluation System Evolved), able to evaluate in a non-destructive way the viscoelastic properties of the tires, is presented. The proposed methodology has been developed by the Vehicle Dynamics Research Group of the Department of Industrial Engineering of the university of Naples Federico II, with the main aim to characterize the compound viscoelasticity directly on the tires, with the possibility to perform the tests both in laboratory and on track [14]. After a brief introduction on viscoelastic phenomena and VESevo device, the author presents a case study about the evolution of viscoelastic properties increasing of its mileage: exploiting the non-invasive and portable nature of the device, it was possible to perform a viscoelastic characterization and to reuse a same tire several times in order to trace the evolution of the Storage Modulus and Loss Factor as the mileage changes, highlighting the differences between the new and used tire and how they affect the vehicle performance and safety, suggesting when the tire should be replaced by a new one.

2 Viscoelastic Properties and Grip Principles

Viscoelastic material is a deformable material with a behaviour that lies between a viscous liquid and an elastic solid. The feature that differentiates these materials from others is that, while in the case of elastic solids and viscous fluids the answer to one effort or instantaneous deformation is also instantaneous and independent of time, in the case of viscoelastic materials it is function of time [15].

This means that the stress-strain relationship is defined by a complex dynamic modulus as the amount of the overall resistance to the deformation of the compound:

$$\frac{\sigma(t)}{\varepsilon(t)} = E^* = E_1 + iE_2 \tag{1}$$

$$Tan(\delta) = \frac{E_2}{E_1} \tag{2}$$

The complex modulus is characterized by a real and an imaginary part. The first one is defined Storage Modulus E' and is an esteem of the elasticity of the material linked to the ability to store energy, the second one is the Loss Modulus E'' and it is associated with the aptitude of the compound to dissipate energy as heat. The ratio of the Loss Modulus to the Storage Modulus defines the Loss Factor which is an index of the material overall damping and one of the key parameters in the studies of tire grip.

Under stress, the behaviour of viscoelastic materials is strongly influenced by both the excitation frequency and temperature, for the latter is proposed a diagram in the Fig. 1. These two physical magnitudes can be correlated applying an empirical equation defined by Willian, Landel and Ferry [16, 17].

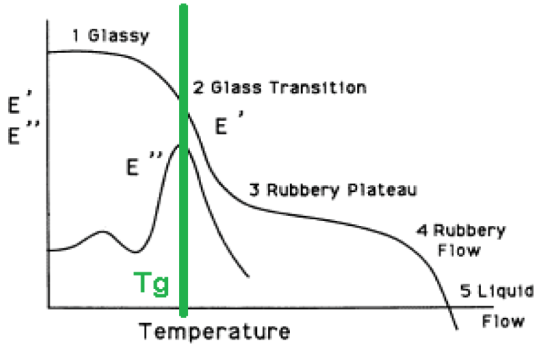

Fig. 1. Storage and loss modulus respect temperature

The knowledge of viscoelastic properties is a key factor in the grip generation, which is defined as the coefficient of friction between the surface of the tire and the surface of the road. This friction depends on an array of factors including the roughness of the track as well as the type, temperature and therefore behaviour of the tire-rubber [4, 18, 19]. In vehicle dynamic field two stress mechanism, shown in Fig. 2, are involved in the rubber-road interface:

- The first mechanism is the frequency excitation of the material by the road texture. The rubber is distorted when it slips over the rough spots on the road, the size of which varies from 1 cm (macrotexture range) to 1 micron (microtexture range). This mechanism is known as the road roughness effect. It is also described using the word indentation, which emphasises the penetration of road roughness into the rubber of the tire tread.
- The second mechanism is molecular adhesion, which comes into play at a scale of one hundredth of micron and is amplified by slippage.

In both cases, the viscoelastic properties of the rubber, and particularly its hysteresis (linked to the Loss Factor), play an important role affecting the tire grip performance [4, 21].

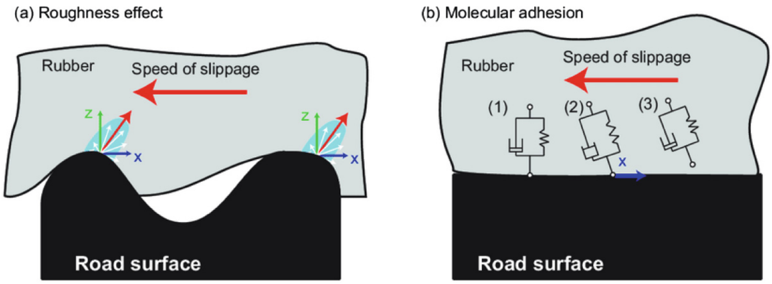

Fig. 2. Friction phenomena: a) Road roughness effect or indentation, b) The molecular adhesion [20].

3 Innovative Device and Testing Procedure

The viscoelastic properties of polymers, such as the tire tread compound, are usually determined by means of D.M.A. However, this method requires a polymeric specimen of suitable dimension which cannot be carried out on systems that do not allow, the realization of the sample required, such as a piece of tread compound of a Motorsport confidential tire. In this scenario, non-destructive procedures are an advantageous solution for the analysis of the tread viscoelasticity, without affecting the tire integrity, allowing a great number of tests in the shortest time possible. An innovative and portable device, defined as *Viscoelasticity Evaluation System Evolved*, commonly known as VESevo [12, 14], which allows users to characterize the tire tread viscoelasticity and its variations due to cooling or heating, due to wear phenomena, aging or different compounding, depending on vehicle applications. Thus, engineers, especially Motorsport ones, are capable to get useful information about their tires, improving the reliability of the data processed by their physical models, and consequently the vehicle performances.

As displayed in Fig. 3 the VESevo device is composed by an instrument for indentation analysis, an acquisition case and a self-made customized software for raw data acquisition.

Fig. 3. VESevo device and acquisition unit

The operation of the device is based on a steel rod with a semi-spherical indenter, which is free to fall and bounce on the surface of the compound to test. The free drop motion of the rod always starts from the same initial position. During each test, the motion of the rod is acquired by an integrated optical sensor, with high frequency response, while a compact IR pyrometer acquired the temperature of the tested compound.

A standardized testing procedure has been set up to perform a single acquisition employing the VESevo; it consists of: the positioning of the device vertically to the tire tread compound or slab; the indenter is manually raised until a mechanical lock in order to obtain each acquisition with the same starting position and velocity; once reached the maximum point, the rod is released thanks to the semi-automatically system and both the rod displacement curve and the compound temperature are shown on the acquisition software.

In Fig. 4, a typical displacement signal is reported, here it is noticeable different phases that characterized the motion of the rod: the drop phase starting from the initial position, the first indentation into the material thickness and, then, the transient bounce until the established contact between the indenter and the tread surface.

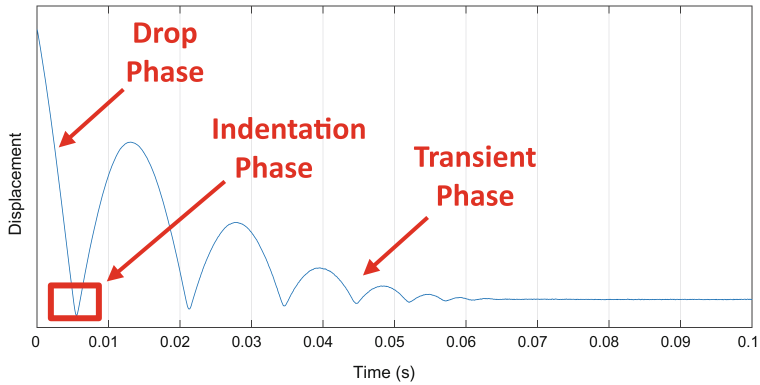

Fig. 4. Acquired raw signal on tire tread surface

In order to investigate the tread compounds behaviour in dependence on the temperature, the tests are performed varying the sample temperature, warming or cooling the material.

The acquired data are then elaborated by a post-processing algorithm capable of analysing each displacement curve at the corresponding temperature and of extrapolating the storage modulus and the loss factor as function of the following magnitudes:

$$E' = f(A_c, T, K_c)$$
$$Tan(\delta) = f(A_c, \omega, T, S_c)$$

where A_c, is the effective contact area between the semi-spherical indenter and the compound, ω is the solicitation frequency linked to the single VESevo test, T is the compound temperature and K_c and S_c are the equivalent contact stiffness and damping coefficient, which can match with the tire tread ones being the VESevo spring stiffness and rod guide negligible.

4 Evolution of the Viscoelastic Properties of a Tire

The testing procedure and the raw signal elaboration, described in the previous chapter, were performed on a tire in order to analyse the evolution of the viscoelastic properties with increasing the mileage.

The tests started by acquiring data on the new tire, which subsequently travelled a distance equal to its mild-life and retested, finally, it travelled a further distance to the end of its life and tested for the last time. The acquisitions were carried out on the central rib in according to the following test-plan: 30 measurements have been acquired at ambient temperature; after that the tire has been cooled down to −20 °C by a freezing spray and 100 measurements have been acquired during the natural heating-up phase of the tire until it reaches almost the ambient temperature; then the tire has been warmed up to 100 °C by a thermal gun and 150 measurements have been acquired during the natural cool down phase of the tire until it reaches almost the ambient temperature.

In Fig. 5, the results of VESevo measurements are plotted at the frequency of 1 Hz, and they are normalized with respect to the maxima values of Storage Modulus (E′) and Loss Factor (tan(δ)).

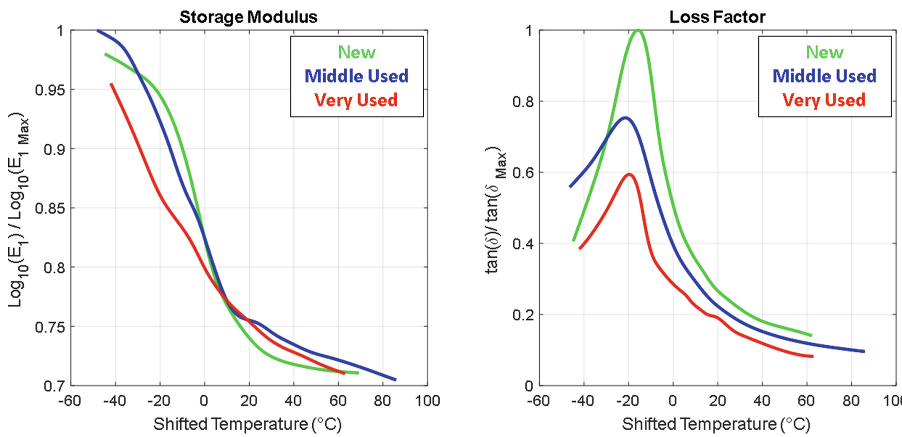

Fig. 5. Viscoelastic properties obtained by means of VESevo

The comparison of the viscoelastic curves highlights the differences among the three tire conditions:

- New-Middle used tire: the middle used curves compared to the new ones display, in term of Loss Factor, a reduction of the values in almost the entire temperature range, and a slightly variation of the temperature of the tan(δ) peak. While, in terms of Storage Modulus, an increasing of the values at temperature above 20 °C. The evolution of the two viscoelastic properties suggests that the middle used tire cannot exploit more good grip performance in both adhesive (linked to the E′) and hysteretic (linked to tan(δ)) terms in high temperature range.

- Middle-Very used tire: increasing the mileage, the loss factor curve highlights a further decrease in the values, generating a worsening of the hysteretic grip. Also in this case the glass transition temperature (linked to the peak of the tan (δ)) does not show large changes on the contrary of the relative value in terms of loss factor. The Storage Modulus exhibits the same evolution of the Loss Factor, displaying a marked reduction for temperature below 10 °C, making it less hard than the previous two conditions.
- New-Very used tire: the comparison between the two opposite conditions shows great differences in both viscoelastic properties, highlighting a great decay of the hysteretic grip, especially in the glass transition zone, due to lower values of the Loss Factor curve (Table 1).

Table 1. Glassy transition temperature comparison

Condition	Glass transition temperature (°C)	Normalized peak value
Very used	−15.90	1
Middle used	−21.70	0.75
Very used	−19.70	0.59

5 Conclusion

In this paper, the analysis of the evolution of viscoelastic properties over the progressive mileage is presented, to highlight the tread performance degradation due to wear phenomena. Such analysis was made possible thanks to the use of an innovative device called VESevo, which is able to characterize the viscoelastic properties of tires without using expensive rheometers, as traditional D.M.A., and not damaging the tested tire.

The results obtained have highlighted important variations between the new and the used tire both in terms of Storage Modulus and Loss Factor, that could be very useful in vehicle dynamic field, from motorsport to truck or passenger applications such as: the improvement of the monitoring of material performance during its whole lifecycle and for comprehending when changing tires configuration could be necessary.

Funding. This work was partly supported by the project “FASTire (Foam Airless Spoked Tire): Smart Airless Tyres for Extremely-Low Rolling Resistance and Superior Passengers Comfort” funded by the Italian MIUR “Progetti di Ricerca di Rilevante Interesse Nazionale (PRIN)”–grant no. 2017948FEN.

References

1. Sakhnevych, A.: Multiphysical MF-based tyre modelling and parametrisation for vehicle setup and control strategies optimisation. Veh. Syst. Dyn. **0**, 1–22 (2021). https://doi.org/10.1080/00423114.2021.1977833
2. Farroni, F., Genovese, A., Sakhnevych, A.: Performance and safety enhancement strategies in vehicle dynamics and ground contact. Appl. Sci. **12** (2022). https://doi.org/10.3390/app12042034
3. Genovese, A., Carputo, F., Maiorano, A., Timpone, F., Farroni, F., Sakhnevych, A.: Study on the generalized formulations with the aim to reproduce the viscoelastic dynamic behavior of polymers. Appl. Sci. **10** (2020). https://doi.org/10.3390/app10072321
4. Genovese, A., Carputo, F., Ciavarella, M., Farroni, F., Papangelo, A., Sakhnevych, A.: Analysis of multiscale theories for viscoelastic rubber friction. In: Conference of the Italian Association of Theoretical and Applied Mechanics, AIMETA 2019, pp. 1125–1135 (2020)
5. Carbone, G., Lorenz, B., Persson, B.N.J., Wohlers, A.: Contact mechanics and rubber friction for randomly rough surfaces with anisotropic statistical properties. Eur. Phys. J. E **29** (2009). https://doi.org/10.1140/epje/i2009-10484-8
6. Lang, A., Klüppel, M.: Influences of temperature and load on the dry friction behaviour of tire tread compounds in contact with rough granite. Wear **380–381** (2017). https://doi.org/10.1016/j.wear.2017.02.047
7. Teodosio, L., et al.: A numerical methodology for thermo-fluid dynamic modelling of tyre inner chamber: towards real time applications. Meccanica **56** (2021). https://doi.org/10.1007/s11012-021-01310-w
8. Menard, K.P., Menard, N.R.: Dynamic mechanical analysis. CRC Press, Boca Raton (2020)
9. Lionetto, F., Montagna, F., Maffezzoli, A.: Ultrasonic dynamic mechanical analysis of polymers. Appl. Rheol. **15** (2005). https://doi.org/10.1515/arh-2005-0016
10. Sakhnevych, A., Genovese, A., Maiorano, A., Timpone, F., Farroni, F.: An ultrasound method for characterization of viscoelastic properties in frequency domain at small deformations. Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci. **235** (2021). https://doi.org/10.1177/09544062211005789
11. Schultz, J.W.: Dielectric spectroscopy in analysis of polymers. In: Encyclopedia of Analytical Chemistry. Wiley, Hoboken (2006)
12. Genovese, A., Pastore, S.R.: A novel nondestructive procedure for tire tread viscoelastic characterization. Tire Sci. Technol (2022). https://doi.org/10.2346/tire.21.19002
13. Genovese, A., Pastore, S.R.: Development of a portable instrument for non-destructive characterization of the polymers viscoelastic properties. Mech. Syst. Signal Process. **150** (2021). https://doi.org/10.1016/j.ymssp.2020.107259
14. Farroni, F., Genovese, A., Maiorano, A., Sakhnevych, A., Timpone, F.: Development of an innovative instrument for non-destructive viscoelasticity characterization: VESevo. In: Niola, V., Gasparetto, A. (eds.) IFToMM ITALY 2020. MMS, vol. 91, pp. 804–812. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-55807-9_89
15. Mark, J.E., Erman, B., Roland, M.: The science and technology of rubber (2013)
16. Ferry, J.: Viscoelastic Properties of Polymers (1980)
17. Landel, R.F.: A two-part tale: the WLF equation and beyond linear viscoelasticity. Rubber Chem. Technol. **79** (2006). https://doi.org/10.5254/1.3547943
18. Genovese, A., Farroni, F., Papangelo, A., Ciavarella, M.: A discussion on present theories of rubber friction, with particular reference to different possible choices of arbitrary roughness cutoff parameters. Lubricants **7** (2019). https://doi.org/10.3390/lubricants7100085
19. Genovese, A., D'Angelo, G.A., Sakhnevych, A., Farroni, F.: Review on friction and wear test rigs: an overview on the state of the art in tyre tread friction evaluation. Lubricants **8** (2020). https://doi.org/10.3390/lubricants8090091

20. Acosta Reche, M., Kanarachos, S., Blundell, M.: Road friction virtual sensing: a review of estimation techniques with emphasis on low excitation approaches. Appl. Sci. **7** (2017). https://doi.org/10.3390/app7121230
21. Le Gal, A., Klüppel, M.: Investigation and modelling of rubber stationary friction on rough surfaces. J. Phys. Condens. Matter **20** (2008). https://doi.org/10.1088/0953-8984/20/01/015007