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A Test Rig for Tyre Envelope Model Characterization

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Abstract — **This paper deals with tyre enveloping behaviour on uneven road surface. To build realistic and reliable vehicle dynamics models it is of fundamental importance to study the influence of road obstacles and irregularities on forces and displacements involving a rolling tyre. After a brief review about early studies concerning this phenomenon, the tandem model with elliptical cams is introduced and described, highlighting its hypothesis and the parameters on which it is based, the most important of which are the cams profiles and the distance between them. The main aim of this paper is the executive project of a test rig aimed to carry out an experimental campaign for the identification of the parameters of the tandem cam model and for its validation.**

The idea is to experimentally acquire the path of the patch centre of a tyre rolling over an obstacle, to define the parameters of the curves employed for the cam profiles and the distance between them in the tandem model. It is important to highlight that these parameters are strictly connected to tyre properties and need tests to be investigated and identified.

The design started from a test bench for motorcycles already available at DII's Tyre Lab, introducing proper changes without compromising original test bench destination.

Index Terms — **Tyre envelope model, Tyre experimental test rig, Tyre ride quality**

I. INTRODUCTION

DURING its real working life a tyre rolls over uneven road and the presence of irregularities generates sudden variations both in tyre position and in interaction forces direction and modulus. This aspect concerns transient performances and is usually not taken into account in vehicle dynamics modelling and simulation [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11] despite it has not a negligible influence on tyre dynamics and then on vehicle behaviour. Moreover, vehicle dynamics control systems [12], [13], [14], [15], [16], [17] are usually based on the hypothesis that the tyre is always in contact with the road and this not always verified assumption can cause their improper intervention. Also tyre friction [18], [19], [20], [21], [22], [23], [24] and thermal modelling [25] are influenced by the effects of this phenomenon.

For this reasons the development of reliable models able to take into account tyre enveloping behaviour on road irregularities is necessary to better understand and simulate the vehicle real performance.

Research on the excitation of pneumatic tyres caused by uneven road surfaces started in the 1960s. Since then, several models have been developed in order to describe the tyre enveloping behaviour, which consists in the capability of the tyre to deform when rolling over small road irregularities. Although many of these models are used as components in dynamic vehicle models, the development of these last started from the late 1980s. Many dynamic tyre models were developed during the last decade as results of growing interest in virtual prototyping with regard to ride comfort and durability simulations.

The research in the 1960s was mainly experimental: Hey [26] stated that little was known about the forces generated between tyre and road when rolling over obstacles. Important observations considering the enveloping behaviour on short obstacle were made by Gough [27], who indicated that a tyre rolling quasi-statically at constant velocity and axle height [28] over an obstacle with characteristic length much smaller than the tyre contact length, shows three distinct responses: (1) variations in the vertical force, (2) variations in the longitudinal force and (3) variations in the spin velocity of the wheel. These responses are shown in Fig. 1.

Gough's test results showed that the duration of the three responses is much longer than the time employed to cross the obstacle. This is due to the visco-elastic properties and geometry of the tyre [29]: because of its curvature in the contact zone, the tyre gets in contact with the obstacle before than the wheel centre overtakes it; vice versa, the tyre is still in contact with the obstacle after that the wheel centre has overtaken it.

In the sketched situation, two contact patches exist: this phenomenon results in a response of the tyre that is much smoother than the obstacle shape, often described as an obstacle filtering.

Lippmann et al. [30] studied the responses of both truck and passenger car tyres rolling over short sharp unevennesses like cleats and steps of several heights. From their experiments, they concluded that an almost linear relation exists between tyre longitudinal and vertical force variations and step height. Therefore, they proposed that the superposition principle could be used to calculate the response of a tyre to any obstacle shape described as the sum of elementary steps.

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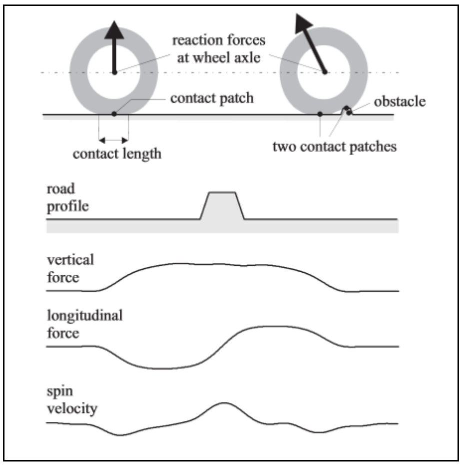


Fig. 1. Variations in the vertical force, variations in the longitudinal force, variations in the spin velocity of the wheel [31] (courtesy of Dr. Antoine Schmeitz).

Later researches have been mainly focused on the development of techniques to model tyre behaviour on road unevennesses. Bandel and Monguzzi [32] discovered that the variations of vertical and longitudinal forces for a tyre rolling quasi-statically over an obstacle could be transformed into the convolution of two identical basic functions by means of empirical relations. They showed that the basic function for a specific obstacle represents a characteristic of the tyre and is independent on inflation pressure and deflection (or vertical load). They also showed the influence of obstacle length and height on the basic functions. This concept was adopted by Zegelaar [33], who used half and quarter sine waves for the basic functions of a cleat and step obstacle. He also introduced an alternative technique for obtaining the effective road surface using a single basic curve and a two-point follower. After having worked with the two-point follower model on quarter sine waves (Fig. 2) and after having understood its limitations, the idea was hit upon to generate the elementary basic curve that holds for a step in road profile with an elliptical cam. (Fig. 3).

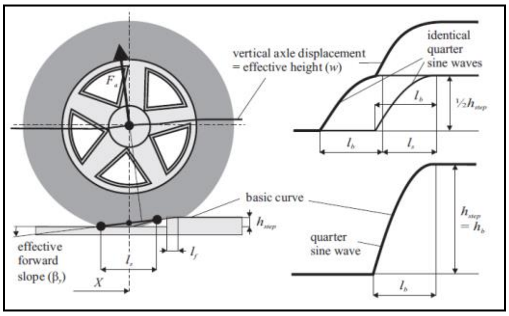


Fig. 2. Representation of the basic function and two-point follower models [31] (courtesy of Dr. Antoine Schmeitz).

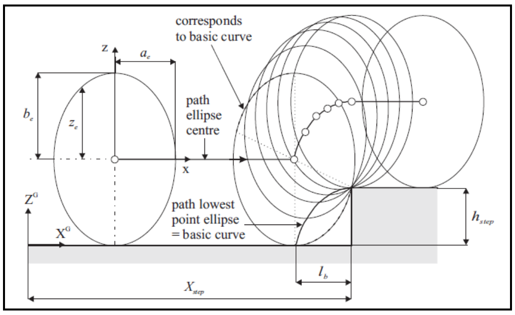


Fig. 3. Generation of the elementary basic curve with an elliptical cam [31] (courtesy of Dr. Antoine Schmeitz).

II. THE TANDEM MODEL WITH ELLIPTICAL CAMS

In order to reproduce the experimental double-bump shaped curve [31], [34], it is necessary to adopt the results provided by the two-point follower solution. It is however more convenient to use a full geometrical model that can move directly over the actual road profile. Since a single elliptical cam moving over the actual road profile is able to describe the basis curve, the effective height and slope can be obtained by moving with two cams in "tandem" configuration over the actual road surface, as is illustrated in Figure 4.

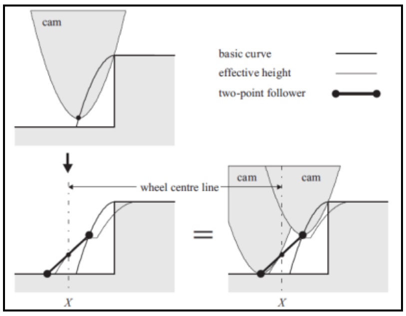


Fig. 4. Two elliptical cams in "tandem" configuration used to generate the effective road surface [31] (courtesy of Dr. Antoine Schmeitz).

The distance between the two elliptical cams *ls* is equal to the length of the two-point follower. The effective height *w* of the contact patch centre is equal to the height of the midpoint of the lower tandem rod (fig. 5). Thus, the equation for the effective height is:

$$w(X) = \frac{Z_f + Z_r}{2} - b_e \tag{1}$$

where X is the global wheel centre longitudinal position and Z_f and Z_r are the global heights of the front and rear ellipse centres, respectively. The inclination angle of the tandem rod corresponds to the effective slope tan(β_y):

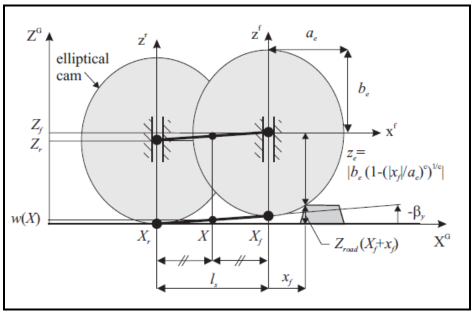


Fig. 5. The tandem model with elliptical cams used to generate the effective road surface [31] (courtesy of Dr. Antoine Schmeitz).

$$tan\,\beta_y = \frac{Z_r - Z_f}{l_s} \tag{2}$$

The main goal of the presented activity is to study the behaviour of a tyre rolling over an obstacle. In order to reproduce analytically the experimental shapes, a first stage of the work concerned with the design of the test bench for the data collection presented in this paper. Further developments will consist in the parametrical identification of the tandem cam model and in its validation on the basis of experimental results.

III. TYRE ENVELOPE TEST BENCH

The idea to assess experimentally the centre's path of a tyre rolling over an obstacle represents in the described activity a preliminary step, useful to define the parameters of the ellipse employed for the cam profile and the distance between them in the tandem model.

It is important to highlight that these parameters are strictly connected to tyre properties, that need tests to be investigated and identified. In order to carry out these experiments, it has been necessary to realize a dedicated test bench.

Since in DII's Tyre Lab a test bench for motorcycles was already available [35], [36], [37] it has been decided to modify and to use it to test car tyres. The pre-existing test bench is shown in Fig. 6. This framework allows to simulate a motorcycle going on an even road surface. Essentially it is composed of a driver belt moved by an electrical motor and of a portal that shores up part of the motorcycle that has to be tested. The idea is to use the other side of the driver belt without interfering with the motorcycle experiments, so that it has been fundamental to build another portal that could shore up car tyre.

The new test bench (Fig. 7) is composed of a portal, of a tyre supporting system and of a device able to apply a load equivalent to the one due to vehicle mass and to load transfers observable in common working conditions. New portal is composed of an upper and two lateral crossbars in Fe510B steel, section bars 60mm x 40mm, fixed to the pre-existing one with bolted connections.

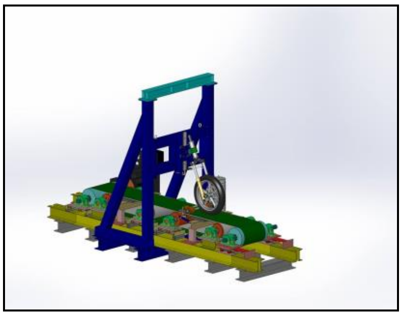


Fig. 6. Pre existing motorcycle test bench.

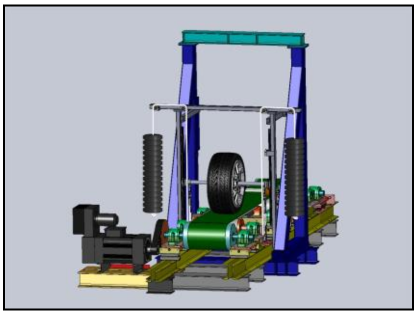
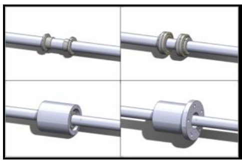


Fig. 7. New car tyre test bench.

Simulating tyre motion needs a system that allows the replication of its real working conditions: in order to make this possible, the tyre has to be able to rotate around its axis and to move vertically. For this reason tyre supporting system is composed by a shaft onto which it is fitted a flange to fasten the rim of the wheel (Fig. 8a), fixed to the portal through two linear guideways (Fig. 8b).

To mount different kinds of rims onto the shaft it has been necessary to realize a proper fitting system, allowing the flange to be interchangeable. The fitting system is composed of two adapter sleeves for shafts, two spherical roller bearings for cylindrical and tapered bore and an axle box fastened on them. Finally, the mounting flange is bolted onto the axle box. It is important to point out that the shaft does not rotate, while the axle box and the flange do. The system just described is depicted in Fig. 8a.



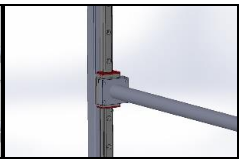


Fig. 8a. Tyre supporting system.
Fig. 8b. Portal guideways detail.

Shaft has been built in a 39NiCrMo3, surface hardened (HRC 55-60, hardening depth 2.00 – 5.00 mm), grinded and chromium plated steel of circular section (Ø 40 mm), for which a stress verification calculation has been done. In order to avoid shaft rotation, its ends have been machined in a square shape (Fig. 9).

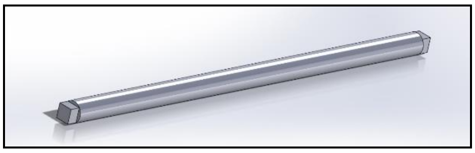


Fig. 9. View of the shaft square end.

The device for load application is composed of two double hoists depicted in Fig. 10, installed at the shaft ends. The lower part of the hoist, composed of two pulleys mounted on a support, is fixed to the base of the structure. The upper part is composed of two pulleys mounted on a support and a welding eyebolt hooked on an element fitted on the shaft.

Since maximum applied load is equal to 6000N on each side of the shaft, a verification of the strength of the hoist's components has been performed.

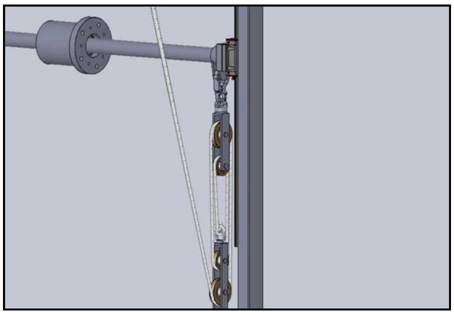


Fig. 10. Double hoist loading system.

IV. EMPLOYED SENSORS AND TESTING PROCEDURE

In order to characterize experimentally the tyre enveloping model, it is necessary to estimate the trajectory of the wheel center and the interaction forces Fx and Fz of the tyre rolling over an obstacle. For this reason the test bench has been equipped with a displacement sensor and eight load cells.

It has been chosen to employ a non-contact laser displacement sensor. Since the idea is to perform experiments at high speed, a contact displacement sensor would have been inaccurate because of the delay related to the inertia of the sensor’s mobile components at high speed. Basing on optical triangulation principle, the laser ray has to point in perpendicular direction to an even surface; for this reason the best mounting solution is to fix the sensor to one of the lateral crossbars of the portal and to point the laser ray to the flange bolted to the guideway’s block.

It has been defined that the optimal procedure to measure the interaction forces Fx and Fz, according to the position of all components of the structure, is to insert eight compression mini-load cells between the square section faces of the shaft and the square section faces of the flange. The load cells, sensitive to compression loads, must be positioned in perpendicular direction so that four cell can measure the vertical load and the other four the longitudinal one.

Once defined and tested the optimal rig setup, the system has been employed with the aim to carry out a wide experimental campaign, able to investigate the dependence of tyre enveloping behaviour on several variables, such as obstacles length and height, load and speed at which the tyre approaches to the obstacle and tyre structure and dimension.

Standard test procedure consists in: (1) sticking the testing obstacle (typically, a kerb for motorsport applications and a step or a rail piece for passenger ones) on the driver belt, (2) putting tyre in contact with the belt and applying load by means of the described device, choosing the proper force on the basis of the nominal load acting on the tyre in common working conditions employing calibrated weights, (3) activating the driver belt, selecting the proper speed, (4) starting data acquisition.

In figure 11 a first experimental result of the wheel centre vertical displacement as a function of the longitudinal displacement is reported. The test has been carried out using a slick high performance tyre with an inflation pressure of 1,85 bar and a vertical load of 4800 N rolling along a flat surface with a cleat 0,03 m high.

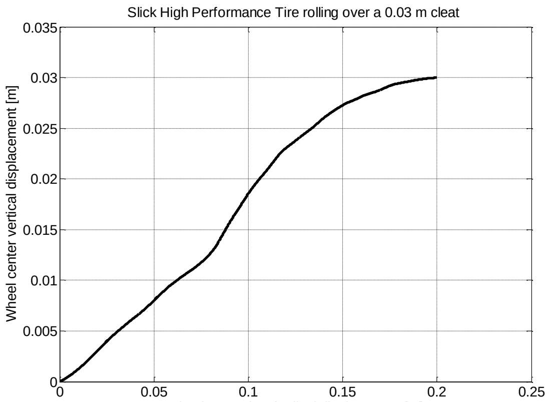


Fig. 11. Wheel center vertical displacement vs longitudinal displacement.

In the figure it is possible to observe the typical experimental double-bump shaped curve [31]. The profile of each single bump is linked to tyre stiffness characteristics, as to inflation pressure. Variations in such quantities reproduce an immediately visible change in the trend of each bump, generally quite linear for high stiffness and high pressure, more curved at lower ones. Curves like the shown one can be used to identify the parameters of the tandem cam models.

It has to be highlighted that rig users are able to act on the test conditions controlling the working variables from a PC located behind a protective glass shield, built in order to respect the safety standards adopted in the laboratory.

V. CONCLUSION

In this paper the final design and the first experimental results of an experimental test rig aimed to characterize the behaviour of a tyre rolling on road obstacles has been presented together with the description of the adopted sensors and of the testing methodology. In particular the test bench is aimed to identify the parameters of tyre envelope models, among which the tandem model with elliptical cams has been preferred, being the most reliable and realistic in this field. Tests are carried out making the tyres roll on a belt on which different obstacles are applied. The obstacles produce changes in tyre center position and in its normal interaction forces, measured by means of displacement and load sensors and sent to a PC. The acquired data are employed as an input for an identification procedure aimed to find out the proper cams profile and distance to reproduce the experimental results. In this way it is possible to understand the influence of tyre constructive properties and of obstacle geometrical dimensions [37] on enveloping model parameters. Future developments of the study will deal with the definition of a specific analytical formulation able to express such influences.

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