"The Art of (Virtual) Rubber Compounding"

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The art of rubber compounding has historically been mastered by a small group of experts with extreme breadth and depth of experience. The rising trend of fluidity between companies is making loyal lifetime "sage compounders" a dying breed and organizations must find new ways to capture and archive experience despite having turnover. Minimizing the time before a new hire becomes productive also becomes critical.

Complex interactions between raw materials and processing make "rules of thumb" insufficient for discovering new technology. These guidelines, even when properly captured, are often over-fit to specific scenarios and can be skewed by human cognitive biases—a disadvantage that is especially detrimental when exploring new technology. Machine Learning, on the other hand, is a method of encoding "experience" based on many observations. Industries that have been revolutionized by data science include algorithmic trading, healthcare, and retail. Just as data has taken the art out of sales and stocks, so too could it allow for more accurate formulation development and reduced cycle time.

Two main challenges affect the amount and quality of data that can be acquired:

a. Many of the standard tests for raw materials are related to verifying material identity and purity rather than predicting compound performance.
b. Even in the largest rubber development laboratories, the number of material-to-compound observations is relatively small compared to the vast amounts of data available in other industries.

These challenges will need to be overcome in order to develop models of structure / property relationships to evaluate, iterate, and tune each component of a rubber formula and quickly react to business needs.

Experimental investigation on the dynamic response of piezoelectric transducer on tyre specimens

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Following the successful work of utilizing piezoelectric transducers in pneumatic tyres, piezoelectric calibration was investigated in this research. In the previous work, which was presented in the TSTCA 2016 and in Tyre expo 2017, an array of piezoelectric transducers were utilized to measure tyre inner liner strain profile to identify tyre rolling characteristics, e.g. tyre rolling speed, tyre vertical load, slip angle and to diagnose any abnormality in the tyre dynamics in rolling conditions. However, the collected s train data were normalized and therefore the recognition criteria were based on the differences in the measured strain profiles. In this work, the piezoelectric signals were calibrated against a controlled excitation platform where a tyre specimen was utilised. These tests were carried out in such a way that the excitation motion was equivalent to the deformation of a pneumatic tyre of a rolling speed up to 30 km/h which is in harmony with the cyclic deformation experienced by the piezoelectric used in the previous studies. A range of calibration tests for the piezoelectric transducer, when attached to a tyre rubber specimen, were carried out over a range of frequencies and amplitudes under uniaxial and torsional loading conditions. The tyre specimen stress, strain and temperature were observed throughout the tests. In addition, the dynamic mechanical properties of the tyre rubber specimen were investigated by observing the phase difference between the measured load and applied excitation on the tyre rubber specimen.

Multi-chamber tyre simulation and tests data for low rolling resistance tyre

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Adaptive tyres benefit from the ability to control the tyre's rolling resistance and grip upon a range of driving and weather conditions. To achieve low rolling resistance in pneumatic tyres under slow rolling speeds, a multi-chamber tyre design was carried out in this study. This tyre has two main modes; economy mode for low rolling resistance properties which is designed to be employed in urban or city driving to reduce fuel consumption and CO_2 emissions, which contributes to the vast majority of passenger vehicles' journey; and a conventional tyre mode in which higher grip and cornering properties are provided.

This multi-chamber tyre has a high pressure chamber next to the tyre rim to provide sufficient support for the outer chambers. The outer chambers are in contact with the tyre tread inner surface. These outer chambers can be independently inflated, so they can provide a range of tyre behaviour for a wide range of driving conditions. A developed tyre model based on the conventional Abaqus software tyre model was utilized to simulate the multi-chamber tyre behaviour. This model shows that tyre vertical stiffness is controlled by the pressure combination in the multi-chamber tyre model.

Following investigation of a range of multi-chamber tyre models and pressure combinations in Abaqus, a multi-chamber tyre prototype was built for the purpose of FEA model validation and experimental characterisation. It was found that this tyre prototype demonstrated that the economy mode actually does provide lower rolling resistance than the conventional mode.

Understanding of Tire Dynamics for Vehicle Ride and ABS Braking Studies

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Abstract

In this study, the excitation of tire rigid belt modes (in-phase, anti-phase, longitudinal and vertical) during vehicle ABS braking and rolling over a cleat are studied. FTire, a high frequency dynamic tire model and a standard vehicle model in CarSim are utilized towards this study. Firstly fundamental understanding of tire rigid belt modes using a simplified 3 DOF rigid ring model is performed, and some important observations on sensitivity of rigid belt modes to tire design parameters (sidewall stiffness, tread stiffness, belt inertia etc.,) are presented. The predictions of 3 DOF results are compared with modes of finite element model. To study these tire design changes on vehicle level (ABS braking and ride), CarSim simulations using FTire models are performed. FTire model parameters corresponding to tire design parameters are adjusted accordingly. Some important observations on importance of tire design parameters during ABS and cleat simulations are reported. Finally, finite element model with a proposed tire design changes is used to create a simplified in-plane dynamic FTire models.

Keywords: Dynamic tire model, FTire, Rigid ring, Belt dynamics, Ride, Cleat, ABS, Braking, CarSim.

“Variable Stiffness Approach to Optimize Tyre Rolling Resistance”

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With ever increasing demand for transportation and mobility, fuel economy has become a momentous subject in automobile industries. Tyre rolling resistance plays a vital role in the fuel economy. This needs to be continuously reduced. Also, the requirement of its further reduction will be of paramount importance in new generation vehicles. Such targets can be met only through the combination of advanced materials and manufacturing technologies coupled with innovative tyre designs.

Previous studies have shown the rolling loss optimization through geometry, compound and construction combinations. Dependence on the profile and construction, forces a limitation of not meeting the target with the chosen materials. This may deteriorate other tyre performance measures in some cases.

Optimal rolling resistance tyre necessitates effective distribution of the rolling loss contributor i.e., the resultant of the stiffness, volume and dissipation. Contribution of the three tyre deformation modes viz., equal strain, equal stress and equal energy on the rolling loss vary with the stiffness. As proposed in the literature, deformation index technique captures these inherent insights and is useful for the rolling resistance optimization. This will give a direction and scope by identifying possible zones whose stiffness can be varied through proper material selection. With continuous advancements in manufacturing technologies, realizing a tyre with optimal distribution of stiffness at different locations will not be far away.

In this study, a novel approach is developed using Finite Element technique to simulate the deformation index along with the rolling resistance prediction by implementing the variable stiffness approach. Studies are carried out on both the passenger car and the commercial vehicle tyres including cross-ply tyres. Potential zones for stiffness variation have been identified and the new designs are proposed accordingly. This approach has resulted in around 10% of rolling resistance improvement depending upon the tyre chosen. The proposed approach thus forms a viable tyre design tool for rolling resistance optimization.

“Optimization of cure cycle and tread compound for rolling resistance reduction of Truck Bus Bias tires”

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Rolling resistance refers to the various forms of resistance against driving force when the vehicle is in motion. Several factors contribute to rolling resistance, including wind drag on the vehicle, acceleration resistance generated by inertia force when speeding up, and resistance on the tires. As a tire flexes when it rotates, due to the natural viscoelastic properties of rubber, friction between molecules causes energy to be converted to heat. This is known as hysteresis loss. Such loss accounts for the majority of all rolling resistance particularly in a bias ply tire than a radial ply tire. Reducing rolling resistance is one of the key performance challenges for all tire and vehicle manufacturers.

The tread's interaction with the road is the major contributor for tire rolling resistance. This paper summarizes the combined effect of tread compound and the cure cycle on rolling resistance characteristics in a bias ply tire. Some real time experiments with different blends of natural and synthetic rubber showed better improvement. This tread compound combined with trying different curing cycle by optimizing the time duration of curing media in the curing press helped to lower hysteresis loss of inner components of the tire and thereby helps to achieve reduced tire rolling resistance without compromising performance characteristics.

“The simulation of the interaction between tire and soil using the discrete element method”

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Mankind has always searched for new ways of improving the system of plantation and harvesting. As a consequence, agriculture has adopted technology in different aspects, since the development of genetically modified seeds up to the use of new and more sophisticated agricultural implements.

The use of agricultural machineries as tractors, grain harvesters and trucks is often attached to the concerns with their impact on the soil and, consequently, on the cultivation of new crops. In that theme, the tire plays an important role since it is the component responsible for providing enough traction to the system and avoiding the soil to be compacted more than the admissible.

Based on this information, the project of the tire should take on account different characteristics that it needs to have to perform well on the field, for example: it should have a self-cleaning tread pattern to remove mud from the tread grooves; it needs to provide enough contact with the soil to ensure the traction even on adverse conditions; it can not compact the soil excessively; it should have high resistance to penetration.

As the years passed and the computational power increased, virtual simulations became a powerful tool to predict the tire behavior and its impact on the soil. The Discrete Element Method (DEM) in association with the Finite Element Method (FEM) can be used to analyze the interaction between the tire and a deformable soil, which can be modeled considering the properties and characteristics of different materials like sand, rock and mud.

This paper presents an analysis of the interaction between tire and soil using the Discrete Element Method and it describes the process of creation of a virtual model in EDEM^R software, including the experimental measurements of the soil properties and some experimental approach to validate it. Besides this, the authors use the model to analyze the effects of some modifications in the tire project on its behavior.

“Experimental Investigation and Simulation of Aircraft Tire Wear”

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Not only in the automotive sector, but also in the field of aircraft tires, the topic of abrasion is of great importance. The tire manufacturers provide criteria for the permissible degree of wear. If these limits are exceeded, the tire must be replaced or retreaded. By this time, the tire should withstand as many takeoff and landing cycles as possible. Abrasion models should help to predict the wear behavior in pre-flight modeling and can help to design the suspension optimally.

At the Institute of Dynamics and Vibrations Research, quasi-steady abrasion tests are performed using tread block samples from an aircraft tire. For various pressures and sliding speeds, the abrasion is determined by recording the mass loss of the rubber sample. Based on these measurement data, a wear model is derived as a function of coefficient of friction, contact pressure and sliding speed.

The brush model forms the basis for the wear simulations. With parameters validated on the aircraft tire, such as contact length, stiffness and friction coefficient, the resulting mechanical forces within the contact area are calculated. Finally, the classic brush model is extended by the abrasion calculation. The tire wear is determined during unsteady load and slip conditions by use of the quasi-steady wear maps derived from the experiments. Within a measurement campaign on the complete tire, the tread depth is measured after various driving maneuvers and is compared here with the simulation results.

Incremental Critical Plane Analysis of FMVSS 119 Tire Durability Testing

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Government regulations for tire makers specify qualification procedures which require crack-free operation of the tire under a schedule of progressively increasing loads. A simulation workflow for computing the effects of such load schedules on durability has been developed using the Endurica CL fatigue solver, combined with a Digital Twin interface (Endurica DT) that enables incremental analysis. The workflow starts with a given series of steady state rolling finite element solutions computed for each of the load steps in the test schedule. For each load step, the corresponding finite element solution is used to compute the incremental progress of crack growth in each element. The crack length at the end of a step becomes the initial crack length for the next step. At the end of each step, a remaining life calculation is also made. The remaining life calculation is based on a reference load case, here taken as 100% load under straight-ahead rolling. The remaining life calculation gives the number of repeats of the reference load case that are required to grow the crack in each element to its end-of-life condition (ie 1 mm crack length). The workflow is demonstrated on a truck tire using the FMVSS 119 testing schedule. In addition to the FMVSS schedule, additional tire usage and abuse scenarios are computed and compared.

“The effects of different tire operating conditions on transient lateral tire response”

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The concept of the relaxation length is often used to describe a tire’s transient response. This paper investigates how the transient response changes with different operating conditions. Through the measurement of tire forces and tire deformations during transient maneuvers performed on an indoor flat belt tire test machine, experimental data have been used to calculate various tire stiffness and tire damping properties. These properties are then compared to results from non-rolling quasi-static stiffness measurements.

Using this methodology, the effects of tire load, inflation pressure, speed, and temperature on these stiffness and damping properties have been identified. The mechanisms behind these effects are discussed and their impact on common transient tire modelling approaches are considered. Finally, a first-order modelling approach is used to evaluate the overall impact of these effects on transient tire and vehicle performance.

"Influence of Vehicle Boundary Conditions on the Forces Transmitted below 400Hz between Wheel and Hub"

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Indoor blocked force measurements of a tire rolling on a drum are commonly used to assess the potential NVH performance of a tire. This test method has many practical advantages including clearly identifiable modes which are relevant for the NVH performance of the tire on a target vehicle. However, the fixed boundary conditions at the spindle are not representative of the hub of a vehicle, and may have a negative impact on the prediction of performance therein.

In this investigation, the blocked forces generated by several different tire constructions are calculated numerically with the FEM. The same tire models are then coupled to a vehicle model to calculate coupled forces due to the same excitation of the contact. An order tracking is then performed with respect to the drum excitation for both cases and the similarities and differences analysed. Special attention is given to the location of natural frequencies and the ranking of forces generated by the different tire constructions.

Finally, the operating deflection shapes of the coupled tires predicted numerically are validated using a Polytec PSV-500 Xtra 3D scanning laser vibrometer. In addition to measuring the velocity field on the entire surface of the tire, the rigid body velocities at the centre of the rim are identified and compared with the FEM.

"Vehicle Dynamics Hybrid Simulation with Physical Tires"

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Hybrid simulation combining an off-the-shelf, vehicle dynamic model with a tire specimen in a flat-belt loading rig provides a quick and effective way to evaluate the influence of physical tires on vehicle handling performance without the need to parameterize and validate a tire force model and with higher fidelity than pure simulation.

An iterative, non-real-time, hybrid simulation technique enables running the vehicle simulation and a single tire specimen in the test rig sequentially so that the combination yields results equivalent to a real-time hybrid system where the vehicle computer model and four physical tires run simultaneously. This method allows the use of a conventional force and moment tire test system and eliminates the requirement for a real-time computer simulation.

Several typical vehicle handling maneuvers were run such as on-center steering and double lane change. Comparison with pure simulation using Magic Formula tire models shows differences not only at the tire force and wheel motion level, but also at the vehicle response level. Correlation between simulation and track test data is improved, especially at higher frequencies.

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Pneumatic tire was born to play a main role in absorbing road asperities and irregularities, conferring comfort to the vehicle passengers. However, as a physical system itself, the tire presents intrinsic vibration modes which are inherent to its nature and construction. Such modes may easily interfere with the car modes, producing resonance. As tire engineers we should avoid this situation at the same time as keeping the remaining functions. A deep understanding of the materials and parameters used in the tire construction is crucial to minimize noise and ensure comfort into the car.

This work presents an exhaustive study of some construction factors affecting tire normal modes in the 30-350 Hz range, where the cavity resonance is directly transmitted to the car cabin in the form of noise and vibration. A sensitivity analysis of the construction parameters affecting the frequency of the normal modes was developed by means of finite element simulations of the tire together with the air cavity. The most important factors were changed within specific values to keep the overall characteristics of the tire and four new slightly modified tires were constructed. Modal analysis was employed to extract the normal modes of the tires and compare with the FEM simulations. Finally, vehicle interior noise measurements were performed to validate the hypothesis.

“Application of Machine Learning Techniques to Tire Related Datasets”

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Machine learning (ML) techniques are increasingly becoming popular to model high-dimensional datasets. The first part of this study evaluates the performance of the state-of-the-art supervised ML regression models on tire performance related datasets. More specifically, we focus on the usage of ensemble methods that are known to provide better predictive performance compared to a single model. Their benefits are commonly associated with their ability to reduce the bias and/or variance in learning tasks. The second part of this study compares the performance of the trained ML model against classical semi-empirical models widely used in the tire industry. Finally, this paper presents a broader framework for the usage of such ML models in an ecosystem of connected and digitized cars.

"Objective Tire Footprint Segmentation Assessment From High Speed Videos"

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The forces applied from the vehicle to the road are transferred through the tire contact patch. Its visual inspection using modern optical equipment and image processing is essential for objective tire performance assessment. Quantitative image-based analysis can be useful for the accurate determination of the tire footprint under various operating conditions. However, the ground truth of the related tire footprint contact area is often not available and depends on various factors, such as image contrast, focus, resolution, depth of field, etc. Therefore, very frequently, simplified empirical methods are used to estimate the contact area. In this work, we present a novel methodology to evaluate the quality of different segmentation methods used to extract tire footprints from various video sequences.

Improvement of physical understanding of tire transient handling behavior

STUDENT PAPER

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Increasing vehicle performance requirements and virtualization of its development process require more understanding of physical background of tire behavior, especially in transient rolling conditions with combined slip.
Literature analysis of physical tire models has detected two relevant issues that require deeper investigation: Bending behavior of the tire carcass body and contact patch shape change in different rolling conditions, including the influence of these effects on tire transient behavior.

This research is aimed to improve current understanding of transient tire handling physics, considering detected weaknesses. It was conducted in three steps.
The first step involves answering the question: What happens in a rolling tire?

Using acceleration measurement on the tire inner liner it was observed that the contact patch shape of the rolling tire changes nonlinearly with slip angle and becomes asymmetric. Optical measurement outside and inside the tire has clarified that carcass lateral bending features significant shear angle.

The second step answered the question: How can these processes be reproduced?

A simulation model with physically justified carcass and tread descriptions was developed considering the observed effects. The model was qualitatively validated not only by tire force and
torque, but also by deformation of the tire carcass.

The third step clarified the issue: How do specific properties of tire influence its behavior and why?

The model-based analysis explained which tire structural parameters are responsible for which criteria of tire performance. It was found that both contact patch shape change and carcass shear angle have low influence on tire lateral force, but have perceptible impact on aligning torque generation.

The main scientific contribution is an improvement of understanding of tire physics in transient handling. This is required in the present day in order to support vehicle development process, to increase driver assistance systems efficiency and to improve road traffic safety.

"Aerodynamic Study of Flow Around a Tire on a Rolling Road"

STUDENT PAPER

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Experimental velocity and streamline measurements of a rolling tire in a small scale rolling road wind tunnel are presented and compared to a computational model. The 150mm x 500mm rolling road was specifically developed to characterize the influence a rotating tire exerts on a free stream flow field. The 0.3m^2 Eiffel wind tunnel included optical access to the volume around the tire to utilize Particle Image Velocimetry (PIV) flow measurements to characterize the flow.

The rolling road is controlled with a 3-phase frequency drive that matches road speed to the free stream air speed within the tunnel up to 160 kph. PIV was used to measure the flow structures around a 1/10th scale (soft rubber) tire, the flow was seeded with an olive oil particle generator, and illuminated with a dual power 532 nm Nd:YAG laser. A high-speed CMOS camera was used to collect image pairs at 15 Hz with a 300 micro-second delay and a computer controlled traverse was used to interrogate the flow in multiple X-Z planes. The data was measured singly and compiled into a time-averaged three dimensional vector profile of the flow within the observed volume. The vector profiles developed from this experiment illustrate a phenomenon known as "jetting," where air is displaced into the free stream at the leading edge tire-ground interface. Vortex shedding, caused by flow recirculation at the boundary layer behind the tire was also observed.

For comparison, a CFD model for the above experiment has been generated using STAR-CCM+ to add understanding to the flow around the rolling tire. These results are compared with those of experimental model. The rolling tire is modeled and simulated for full-tire condition where the road surface is taken as moving surface with given velocity. Experimental and computational velocity measurements and streamlines around the rolling tire are compared. A plot is generated from the CFD model for Drag force, Side force, Downforce and Residuals.

“Test and Simulation analysis of Tire Inflation Pressure Loss”

STUDENT PAPER

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Tire inflation pressure loss would be inevitable during tire service time. IPLR (Inflation Pressure Loss Rate) is used to estimate the tire inflation pressure retention performance. A lower IPLR means that tire has a better capacity in maintain tire inflation pressure, which is crucial to vehicle fuel consumption, may thus reduce CO2 emissions. However, an IPLR test is a time-consuming process that 42 days for passenger car tire and 105 days for truck bus tire. In this paper, based on Fick law a finite element model is developed to predict IPLR effectively.

The inflation pressure loss is usually considered as a steady state process. In fact, the rate of gas diffusion would decrease with inflation pressure loss. Ideal material method, based on a creative assumption that a solid material exhibits gas properties, is developed to reveal the relationship between pressure loss and mass diffusion, then realized the transient simulation of inflation pressure loss.

The isotropic diffusion properties were used for the cord-rubber system in previous researches. In this paper, the anisotropy diffusion properties of the rubber-cord composites are determined through differential pressure experiment combined with virtual experiment simulation. Compared with standard IPLR test the difference between the tire IPLR test and the simulation result is within 5%.

"Comparison of analytical models for contact mechanics parameters with numerical analysis and experimental results"

STUDENT PAPER

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Being able to estimate tire/rubber friction is very important to tire engineers, materials developers and pavement engineers. This is due to the need for estimating forces generated at the contact, optimizing tire and vehicle performance and estimating tire wear. Efficient models for contact area and interfacial separation are key for accurate prediction of friction coefficient. Based on the contact mechanics and surface roughness, various models were developed that can predict real area of contact and penetration depth/ interfacial separation. In the present work, we intend to compare the analytical contact mechanics model using experimental results and numerical analysis. Nano-indentation experiments are performed on the rubber compound to obtain penetration depth data. Finite element model of a rubber block in contact with a rough surface was developed and validated using the Nano-indentation experimental data. Results for different surface roughness and operation conditions obtained from the developed finite element model are compared with analytical model results and further model improvements will be discussed.

“Prediction of Pavement Texture and Deformation Influence on Rolling Resistance Using Finite Element Analysis”

STUDENT PAPER

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Rolling resistance, in the phenomenon of tire-pavement interaction, is defined as the force resisting the motion of the tire rolling over the pavement surface. Being considered as one of the causes for the greenhouse emission and fuel consumption of the vehicle, many technologies related to tire manufacturing have been developed in order to purposefully reduce the rolling resistance. From the pavement engineering perspective, rolling resistance can also be reduced by better pavement design during construction and mix design phases. Previous research studies indicated that some measures (such as utilizing pavement surfaces with lower texture depth) may reduce the rolling resistance, however, it may also decrease the skid resistance. Therefore, the accurate evaluation of the rolling resistance considering its potential influential factors is of significant importance both for road authorities and tire industries.

It’s generally believed that the magnitude of rolling resistance depends largely on the surface characteristics of the contacting surfaces, the deformed configurations of the contacting bodies and their material properties. Many previous finite element studies have been conducted to quantify the rolling resistance, but to the best of the authors’ knowledge, none of the studies realistically considered above mentioned factors into their tire-pavement interaction models. This study proposes a practical and realistic approach to consider these factors by developing a thermo-visco-mechanical finite element (FE) models. The developed FE model was validated verses the measured data. Furthermore, influence of tire operating conditions and ambient temperature on the rolling resistance is highlighted.

Obtaining Operating Shapes of a Rotating Tire using Digital Image Correlation

STUDENT PAPER

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Studying the dynamic characteristics of tires is critical because tires can transfer the road excitations to the axle and eventually induce vibrations and noise in the vehicle. Recently, digital image correlation (DIC) has provided a non-contact technique to measure vibrations of structures during operation. The current paper studies the feasibility of using DIC to measure full-field dynamics of tires in rolling conditions. In this work, the Kettering University's FSAE car is placed on a dynamometer to study the dynamics of a racing tire. The tire rotates on the drum roller of the dynamometer and the response of the tire in different speeds is captured using a pair of high speed cameras. The images are processed to obtain the operating deflection shapes of the tire. The obtained shapes are compared to mode shapes obtained using conventional measurement technique. It is shown that DIC provides a robust measurement technique to capture vibrations of rotating tires, which is very challenging using conventional measurement techniques.