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ADVANCEMENTS IN FINITE ELEMENT ANALYSIS FOR TIRE PERFORMANCE: A COMPREHENSIVE REVIEW

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ABSTRACT:

Tires are important components of vehicles and the force between the vehicle and the ground is transmitted through the tires. So, they have a significant effect on the vehicle's performance such as ride, traction, braking, and handling. Traditional tire design is mainly based on theoretical design, which is heavy in workload, long in time consumption, high in cost, and low in accuracy, and is difficult to fulfill the demands of fast expansion of the tire industry. With the advancement of finite element analysis (FEA), finite element simulation models have been widely used in tire mechanics research to predict tire behavior, to refine design of tires and improve tire safety, performance, and durability. This comprehensive review presents recent developments in finite element technology which have high potential for application to tire failures and better understanding of modeling needs of tires.

Keywords: *Finite Element Analysis, Tire Performance, Tire Mechanics, Material Properties, Rolling Resistance*

INTRODUCTION

In the modern era of transportation, with its increasing reliance on automation combined with our use of industrial-scale machinery, tires are an important part of vehicle behavior, safety, fuel economy, and passenger comfort. The tires also absorb the vibrations due to the uneven road surface [1]. As the complexity of tire design continues to grow due to the increasing demand for better performance, efficiency, and reliability, traditional methods of tire testing and optimization are becoming inadequate. Testing tires physically is expensive, time-consuming, and limited in its applicability, especially when trying to inform how tires will perform under extreme temperature conditions, at high speeds during cornering, or under different conditions of load pressure. Computational methods, including FEA, are therefore critical to all aspects of tire design [2].

FEA utilizes the Finite Element Method (FEM), a mathematical procedure that breaks down complex physical systems into smaller, more manageable components (elements), each of which can be treated individually and then assembled into a seamless mathematical model of the entire system [3]. FEM enables detailed predictions about the behavior of the system under various conditions, including stress, strain, deformation, and how it interacts thermally with the rest of the system and its surroundings. In a computational simulation, engineers can predict how a tire will behave in real time under a variety of operating conditions. This approach entails examining the interplay of the numerous physical components that make up the system. Learning how a tire will perform under specific road conditions at high speed, for example, helps engineers program the car's computer accordingly for optimal performance, safety, and durability. Tires are a key part of automobile technological design; without them, a car would be much less comfortable to drive and drastically less safe in most road conditions.

Tire design using FEA has seen significant growth in the past decade, due to the availability of these computational tools and advanced computational power. From simple laptops to powerful supercomputers, engineers are able to simulate tire geometries and study the tires' multi-physics interactions, such as (but not limited to) structural mechanics, heat transfer, fluid dynamics, and vibration analysis. The simulations would help understand how the tire will behave under various conditions ranging from everyday driving to extreme stress scenarios in industrial and aerospace applications.

With FEA, tire development now enables modeling real-life environments with extreme precision, allowing engineers to design for safety, durability, fuel efficiency, comfort, and noise reduction while reducing the cost of development. FEA also offers its advantages in any industry where physical testing is not feasible or the cost of failure is simply too high. For instance, in the aerospace and high-performance automotive industries, FEA can be used to model the dynamics of landing gear and the thermal management required for tire wear.

THE ROLE OF FEA IN TIRE DESIGN

FEA, which today is the foundation of tire design, simulates the interaction between the tire and its environment and operational parameters to an unrivalled degree. The geometry of a tire is divided into an elemental mesh of nodes and elements that interact and are subject to differential equations to calculate its behavior against different forces and stresses. Tire components—the tread, the sidewall, and the bead—have different behaviors, and the sum of these parts affects the overall performance of the tire [4].

FEA Testing Techniques

In particular, FEA can be used to test a tire design in several different ways, catering to the different challenges it faces.

- *Static Analysis*: Statistically describes the tire's performance under constant loading, such as the weight of a car parked on it or a steady-state load at a constant speed [5].
- *Dynamic Analysis*: Using time-varying forces such as those experienced during acceleration, braking, or cornering [6, 7].
- *Modal Analysis*: Predicts how that tire's natural frequencies will affect vibrations, both in terms of performance and comfort [8].

These techniques enable the engineer to tune the tire design across one or more performance criteria until all criteria have been satisfied. The result is the safest, most efficient, and most durable design possible [8, 9].

Benefits of FEA in Tire Design

Due to FEA's flexibility, the same algorithms can be used to simulate everything from micro-scale material properties to macro-scale entire system-level full tire simulations. The primary advantages of implementing FEA in tire design are:

- *Simulation of Complex Geometries*: Tires are composite systems in that they consist of a number of different layers, each with different material properties. FEA models systems that could never be tested on a rolling rig. In an FEA simulation, each material can be described and modeled separately [8].
- *Multiphysics Simulations*: Modern FEA tools can run 'multi-physics' simulations that account for multiple physical phenomena at once, such as thermal expansion, material deformation, and fluid dynamics, simulating the entire system's behavior in the real world [8, 10].
- *Reduced Need for Physical Prototypes*: By simulating a tire's performance with FEA, manufacturers gain the ability to analyze a tire before it is even built, thus reducing their dependency on physical prototypes, which are expensive and time-consuming to make [8].
- *Optimized Performance*: FEA enables engineers to 'virtually test' the tire for failure points by providing valuable design and performance information and helping to create an optimal tire design for performance, safety, and longevity, which in turn improves mileage per gallon and reduces CO_2 emissions [8, 9].

Applications of FEA in Tire Design

Further to the automotive, aerospace, and industrial sectors, FEA has proven to be a vital tool for tire design by mitigating degradation and improving performance, reliability, and safety.

- *Automotive Engineering*: FEA is used to forecast road-surface interactions with tires, optimize rolling resistance to reduce energy consumption, and ensure crashworthiness in impact scenarios. It also plays a role in the development of passive safety systems, including anti-lock braking systems (ABS) and electronic stability control (ESC) [8, 10].
- *Aerospace Engineering*: Aircraft tires are subject to severe and varied conditions (rapid acceleration during takeoff, heavy loading during landing, temperature and pressure variations at high altitude), and their failure could be catastrophic. FEA helps to design tires that can maintain grip and durability in such an environment [9, 10].
- *Industrial Applications*: Engineers can use FEA to design tires for construction and agricultural machinery, as well as mining trucks, which have to function under very high load and pressure in extreme environments [9, 10].

BASIC STEPS FOR IMPLEMENTING FEA FOR TIRES

Using FEA for modeling tires involves several key phases that will all play an important role in the accuracy and stability of the simulation. Following are the common steps for FEA implementation for tires:

Define the Tire Geometry

FEA tire modeling begins with geometry determination of the tire. It involves generating an exact 3D rendering of the tire and all of its pieces, including the tread, sidewall, and bead. Determining the correct geometry is the key to accurate simulations [10, 11].

Meshing the Tire Model

Once the tire geometry has been set, it is time to break down the model into more manageable pieces (meshing). The meshes are important since they have a strong impact on the quality and performance of the FEA simulation. This mesh must be granular enough to represent the fine-grained behavior of the tire but not so granular as to be computationally expensive [10].

Define Material Properties

Tires are constructed of different materials that have varying mechanical properties. It's crucial to be able to specify such material properties accurately in order to perform realistic simulations. That includes specifying the elastic, plastic, and viscoelastic character of rubbers and auxiliary substances in the tire [10].

Apply Boundary Conditions and Loads

Boundary constraints and loads are incorporated in this phase to simulate real-world situations of use for the tire model. This entails generating forces, pressures, and limitations that the tire would feel in activity. These are essential conditions to properly specify in order to produce meaningful simulation results [10].

Implement Tire-Road Contact Algorithm

Simulation of tire-road surface interactions is a challenging, but necessary, step in FEA. A tire-road contact algorithm computes the shape of the tire and its interaction with the road in various roughness and friction levels [10].

Perform Static and Dynamic Analysis

Static and dynamic FEA is used to determine how well the tire will perform in different environments. While static analysis focuses on how the tire behaves at constant load and dynamic analysis on how the tire behaves under time-varying forces (for example acceleration, braking, cornering) [10].

Validate the FEA Model

An important step in model development is validation—irrespective of the numerical values, the FEA model must capture the essential features of how the tire behaves in reality. That means comparative checks of the simulation results against experimental data or benchmarks. Validation might include static footprint analysis, vertical and lateral stiffness, as well as dynamic tests such as the ride [10].

Optimize the Tire Design

When the FEA model has been approved, the design of the tire may be optimized. It consists of tweaking the design specifications to improve performance metrics like roll stiffness, corner stiffness, and durability. Optimizing reduces the risk of a failure and increases the performance, safety, and efficiency of the tire [10].

HISTORICAL TIRE FAILURES AND THE PREVENTIVE POTENTIAL OF FEA

Some of the transportation incidents with tire failures being the cause in which FEA could have averted the accidents by pointing out the structural flaws or failure modes of the tires:

Ford Explorer/Firestone Tire Controversy (1990s)

In the 1990s, the US corporation Firestone manufactured tires for the Ford Explorer SUV, despite warnings from engineers, and hundreds of people died and were injured because the tires failed at high speed. Models P235/75R15 ATX, ATX II, and Wilderness AT (for all terrain) had notably higher failure rates than other models due to tread separation (wherein the tread of the tire is released from the main body of rubber). The TREAD (Transportation Recall Enhancement, Accountability, and Documentation) Act of 2000 was in large part a response to this controversy and to the need to prevent similar failures in the design and manufacture of tires [12, 13].

What the FEA might have revealed: FEA could have been used to model tire behavior under different scenarios—from high speeds to extreme loads. Testing tread separation and other failure modes could have led to the early identification of design defects, potentially allowing for safer tire designs and improved manufacturing standards.

Concorde Crash (2000)

On 25 July 2000, the Concorde jet Air France Flight 4590 crashed minutes after take-off from Charles de Gaulle Airport in Paris. All 109 people on board and four persons on the ground were killed. The crash was a result of the aircraft operating over debris on the runway that caused it to lose a tire, which then exploded and de-integrated. The tire fragments punctured the landing gear and ruptured a fuel tank, causing a leak in the tank that caught fire from the skyrocketing heat generated in the engine compartment. The fuel then leaked out, triggering a lack of thrust in two engines and making it impossible to control the aircraft. As a result of the accident, there were extensive changes made to the Concorde, including reinforced electrical controls, Kevlar tank linings, and specially designed-for-purpose burst-resistant tires [14, 15, 16, 17].

What FEA Could Have Done: With the capability to model the effect of the tire debris striking aircraft components, FEA would have been able to predict where vulnerable design features might exist in the Concorde’s landing gear and fuel tank. By identifying areas of higher stress and failure, FEA could have guided the design of more robust components.

Goodyear G159 Tire Failures on RVs (2000s)

Goodyear’s G159 tire, used on RVs, contributed to an unusually high number of accidents, injuries, and deaths because it overheated and failed at highway speeds. Goodyear knew the G159 was an inappropriate tire for RVs but continued to market it anyway and has already incurred more than 98 injury and death claims. The G159 failed at a much higher rate than other defective tires and led to more than a dozen injury and death lawsuits and several governmental and industry investigations. Goodyear eventually stopped selling the G159 and replaced it with a more robust motorhome tire [18].

What FEA could have done: FEA could have been used to study the tire's thermal and mechanical behavior under the kind of loads and speeds that would be experienced in 'normal' RV operation. Through simulation, engineers could have determined whether a different tire design might be better suited to recreational vehicles and could have avoided the high failure rates that characterized the G159.

Michelin Truck Tire Blowout (2012)

Michelin was hit with considerable criticism in 2012, following a series of tire blowouts of its LTX M/S2 truck tires. Michelin recalled nearly 100,000 tires, fearing that the product would blow out under a heavy load [19].

What FEA could have been used for: FEA could have been used to analyze how the tire was likely to break under a number of loading scenarios, including the presence of high loads and high speeds. If, as the team who made this tire didn't do, stress concentrations and other potential failure points had been identified, then the design of the tire can easily be improved to be safer and more reliable. This may well have prevented the need for a mass recall of a popular product.

Formula 1: 2021 Azerbaijan Grand Prix Tire Failures

In the 2021 Azerbaijan Grand Prix, a series of dramatic tire failures affected the race. The high-speed blowout that Max Verstappen sustained six laps from the conclusion of the race led in an accident that lost him of victory, and Pirelli, the F1 tire manufacturer, later ascribed the blowouts to debris on the track, not production problems.

What FEA should have been used for: FEA could have been used to simulate the tire performance in its operating conditions on the street circuit (with real debris and high-speed cornering).

The historical tire failures discussed above underscore the critical need for rigorous design, manufacturing, and maintenance standards to ensure safety. FEA offers significant potential in predicting and preventing such failures by simulating various stress conditions and identifying vulnerabilities before they lead to catastrophic outcomes. By leveraging FEA, manufacturers can enhance tire safety and reliability, ultimately saving lives and reducing accidents.

OVERVIEW OF PAST RESEARCH ON FEA OF TIRES

Studying the FEA of tires has been a tantalizing topic in the automobile industries for many years, especially in the past 10 years. Fig. 1 reveals the trend of this type of study from 2015 to 2024, with the number of articles published per year.

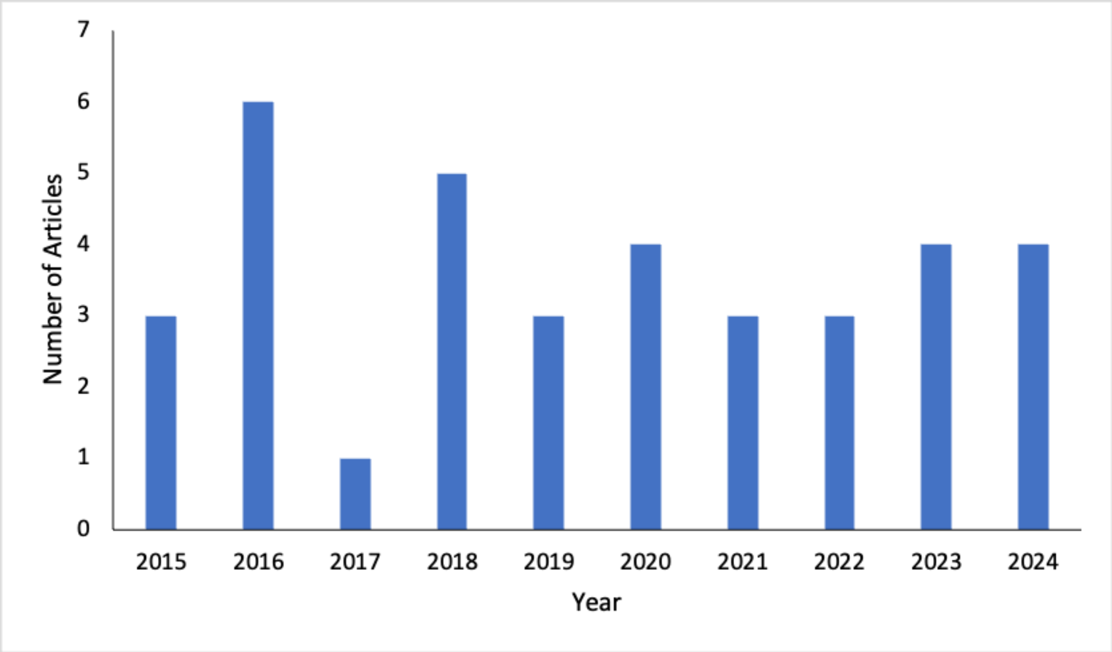

Fig. 1: Number of Articles on FEA of Tires vs. Year

Different publishers have played key roles in disseminating research on this topic. Table 1 below highlights the publishers, and the number of their articles reviewed in this paper.

Table 1: Number of Articles on FEA of Tires by Publisher

Publisher	***Number of Articles Reviewed***
Springer Link	7
Elsevier	5
MDPI	4
SAGE Journals	4
Taylor & Francis	4
GEOMATE Journal	2
Scientific.NET	2
ASCE Library	1
Emerald Insight	1
Engineering Journal	1
IJSRST	1
IOPScience	1
SAE International	1
Scientific Research	1
SJST	1
Total	**36**

A finite element model was created specifically for tire cords by Cho et al. (2015). These authors prescribed equivalent cord models more accurate than traditional models, especially in the belt region of the tire where cracks mostly initiate. The result confirmed that accurate cord modeling improved durability assessments and tire design [20]. Meanwhile, Kazemi et al. (2015) created a computationally efficient tire model in a non-rotating reference frame to simulate vehicle ride and handling. This reduced the degrees of freedom (DoF) of the model while retaining the essential characteristics of the tire, thereby making it more viable for dynamic vehicle simulation [21]. Chauhan et al. (2015) simulated the performance of a tire and wheel assembly impact test, with validations done using strain measurements in the wheel and design modifications explored to enhance the wheel's impact resistance [22].

Patel et al. (2016) proposed a new computational framework for tire modeling called Absolute Nodal Coordinate Formulation (ANCF) finite elements. In this paper, the authors introduced how a tire model can be built for multibody system (MBS) applications with a focus on novelization of existing techniques for improvement in the representation of tire behavior using continuum-based concepts (for vehicle dynamics simulations) [23]. In comparison to the previous paper, Ozaki and Kondo (2016) focused on an anisotropic frictional interaction model within FEA applied to off-road vehicle travelling performance. The results of this study provided interesting insights into the behavior of the interaction of the tire with the ground. The findings suggested that the use of an anisotropic friction model within an FEA significantly improved the accuracy of vehicle performance prediction (drawbar-pull and side forces). Hence, it would be expected that a solution for such a formulation would improve the prediction of performance assessment results, given the reduction in computational cost [24]. In the study provided by Meles et al. (2016), the usage of tire-derived aggregate (TDA) as a material for the building of highway embankments was studied. The authors proposed a nonlinear elastic material model, validated by FEA and full-scale field experiments. The findings of this work helped to confirm the use of the TDA as a construction material that could potentially be applied to practical civil engineering projects, and interesting design guidelines for the construction of new embankments were provided as well [25].

Jeong (2016) investigated how the burst pressure of the radial truck tire can be predicted, quantitatively showing the key part responsible for a pressure-initiated failure to be the steel bead wire. His simulations correlated strongly with hydro-testing data, and his finite element model predicted that the structural integrity of the tire is of paramount importance for tire safety as well as for design optimization possibilities [26]. In a stark contrast, Gungor et al. (2016) quantified the effects of wide-base tires (WBTs) on pavement responses versus dual-tire assemblies (DTAs) in detailed simulations. WBTs can result in more pavement damage, all giving valuable linear equations that could be used in future studies and applications in the field of transport infrastructure engineering [27]. Krmela and Krmelová (2016) focused on enhancing the performance of tires with innovative materials for the steel-cord belt, using FEA to maximize the geometric architecture of reinforcements. These findings suggested that orthotropic cells could, in fact, replace classical steel-cord architectures; moreover, they provided solutions for problems related to the simulation of complex tire components, leading to further explorations on different design options for tires [28].

The investigation by Yao et al. (2017) on the aircraft tire was focused on designing a finite element model that is capable of predicting different performance under loading conditions by reducing the stress within important regions of the tire. The model was validated using experimental data, and a set of safety criteria was defined. These safety criteria are met during the landing to ensure safety, and the model provided a predictive tool for the manufacturer to improve the tire design and safety [29]. On the other hand, Pewekar and Gaikwad (2018) studied hexagonal cellular spoked non-pneumatic tires (NPTs) for automobiles. They evaluated the deformation mechanism of the tire under various loading conditions. The structure was shown to perform well under the loading condition; the stiffness can be improved by changing the shape of the spokes to improve the durability of the tire. These findings highlighted the need for this design to develop further, thereby making the design incomplete in its present form [30]. Phromjan and Suvanjumrat (2018a) turned to solid tires, where the material characterization was done by using the Ogden model and the accuracy of the model is tested experimentally. Their research showed the non-linear deformation of different layers of the tire under quasi-static loads, which may provide explanatory advantages for designing future solid tires [31].

The paper by El-Sayegh and El-Gindy (2018) used FEA combined with the method of Smoothed Particle Hydrodynamics (SPH) to simulate cornering of a truck tire at different depths of water. The results clearly showed that cornering stiffness remains almost constant with an increase in depth of water, while self-aligning moments increased significantly. Results of simulations in this article were validated against experimental datasets [32]. Rugsaj and Suvanjumrat (2018) use NPT, the Michelin TWEEL in particular, to develop hyper-elastic material models. The study reported that the Mooney-Rivlin model was the best to describe the tensile behavior of the TWEEL, with an average error of 17.07 percent, while the Ogden model performed better in compression, with an error of 5.61 percent. This work was a crucial step in novel NPT developments as the accuracy of material modeling is fundamental [33]. Phromjan and Suvanjumrat (2018b) also employed hyper-elastic material models to define solid tires. The authors reported that the Ogden model was effective in describing the stress-strain relationships in different layers of solid tires. For rubber specimens and solid tires, the estimated average errors are 18.00 percent and 14.63 percent, respectively. In summary, this work demonstrated that the Ogden model could be a useful tool to predict mechanical characteristics or failure loads [34].

Rafei et al. (2019) focused on tire rolling resistance, and they did this by looking at the effects of material properties and viscoelastic models. Their best-fit solutions for the tire rolling resistance models indicated non-linear viscoelastic models were more accurate; they furthermore showed that damping characteristics and sipes stiffness could be optimized to enhance tire performance and fuel efficiency [35]. By contrast, in Farhadi et al. (2019), examined the point contact interaction between treaded tires and clay-loam soil; they found that the tread design had a significant effect on traction and displacement of the soil. They also emphasized the important role of tread depth and soil moisture in tire performance, which had direct implications for both agricultural and transportation applications [36]. Rugsaj and Suvanjumrat (2019) examined an NPT, and they developed a 3D model to optimize the spoke thickness under various vertical loads. They found that a spoke thickness of 5 mm maximized vertical stiffness, where this was shown to be a good approximation of the performance of pneumatic tires [37].

Behroozinia et al. (2020) study smart tires to increase road safety based on real-time road information by using FEA to model tires under different loads and road conditions. Their results showed that smart tires could be used to predict road surface friction and load and have important implications for future driver-assist systems and car safety in general [38]. Also, Wei et al. (2020) studied truck and bus radial (TBR) tires using FEA to measure the stress, strain, and energy distribution through the tire's cross-section. Their results defined critical points of failure (bead and shoulder) and validated the model with experimental data in order to demonstrate its practical applications for future tire tuning [39].

Suvanjumrat and Rugsaj (2020) studied a dynamic finite element model of a NPT to evaluate ride comfort and dynamic behavior with a range of element sizes, including types of 3D hexagonal and 2D quadrilateral elements, in conjunction with a visco-hyperelastic model. The results from their study showed that the ride quality of a NPT could be equal to that of a traditional tire, while therefore suggesting the effectiveness of the model in simulating tire-road interaction [40]. Phromjan and Suvanjumrat (2020) engineered the steel belt layers in airless tires and changes in modeling efficiency whereby REBAR elements and homogenization methods are employed. The results indicate that the homogenization method exhibited greater accuracy when considering vertical stiffness results, while both REBAR and homogenization approaches could fairly well simulated performance under compressive load [41]. Phromjan and Suvanjumrat (2021) presents the finite element model developed for solid tires, particularly for forklift applications, whereby the stress-strain characteristics of various rubber compounds under compression are at the heart of this study. The finding suggested that the developed model provides a good fit with experimental data when it comes to simulating the deformation behavior and footprint characteristic under load [42].

Rugsaj and Suvanjumrat's (2021) main goal was to find a dynamic finite element model to describe the mechanical behavior of NPTs under rolling load. They looked at stress and deformation behavior and demonstrated that dynamic loading tended to create many more stresses than static loads and verified their model with experimental data with an average error of less than 4% [43]. On the other hand, the Sufian et al. (2021) study focusing on tire tread design and tire-road contact via FEM revealed that tread design had significant consequences for stress distribution and contact behavior. They observed that vertical tread design increased stress values and larger contact surfaces, improving driving stability [44]. Phromjan and Suvanjumrat (2022) addressed the effects of spoke structure in NPTs, i.e., vertical stiffness and stress distributions in the TWEEL model. They found that the difference in spoke geometry affected both the ride quality and fatigue, while the dynamic stress was higher than the static stress, suggesting durability concerns for certain configurations [45].

The report by Nojumi et al. (2022) showed the effect of new generation wide-base tires (NGWBT) vs. DTA on pavement damage, with a focus on the cold environment. The authors suggested that NGWBT results in higher strain, which can lead to more damage, especially in weaker structures. Thus, results highlighted the need for adjustments in the design of pavements [46]. Rugsaj and Suvanjumrat (2022) dealt with NPTs and examined the effect of spoke geometries on tire stiffness and stress distribution. The authors concluded that careful optimization of spoke shapes could influence tire performance and durability via reduction in concentrations of stresses [47]. Fathi et al. (2023) investigated the cornering behavior of a truck tire under various operational conditions. It showed that tire inflation pressure and the slip angle had a significant effect on the tire lateral forces and vehicle handling, allowing for predictions that improve safety and handling [10].

Zhang et al. (2023) carried out a study on the modeling of tire-pavement contact behavior with finite element model and response surface methodology (RSM). They used the Box-Behnken design for the trial and verified the model using ANOVA. The modeling results under different static and dynamic situations showed a good agreement with the real values, with differences below 5%. The study would allow a better understanding of the pavement reactions in a range of traffic situations and assist in the development of the improved pavement design and care [11].

Yoon et al. (2023) examined the effect of mechanical qualities of tread materials on moving tire sounds. They found that tire tread materials with higher storage and loss moduli increased the structure-borne noise. They further stated that the cushioning property of tires can be changed by improving the viscoelastic properties of the tire materials for the best engineering design of tires to reduce noise. It was crucial that automobiles, particularly electric and autonomous ones, become quieter [48]. Ge et al. (2023) investigated the effects of turning parameters on rolling resistance in complicated tread tires, including camber angles and slip. They claimed that although there is a reasonable correlation between rolling resistance and lateral forces, there is a larger correlation with tire angles. In fact, this can be used for improving tire structure and changing of frame settings for car energy efficiency [49]. The FEA was used by Fathi et al. (2024) to simulate a model of a passenger car tire which conducts an investigation on the rubbers' mixture behaviour due to the fact that the material model considered in this study was the Mooney-Rivlin. With the use of static and dynamic testing, such as the footprint and drum-cleat tests, the researchers validated their model and reported that the filling pressure and vertical load greatly affected the tire-road contact area and tire displacement [9].

Rugsaj and Suvanjumrat (2024) presented a three-dimensional design and study for an NPT with a distinctive X-shaped spoke structure. They examined the load capacity, vertical stiffness, and dynamic performance based on stress, strain, and movement graphs. The model results showed the sturdiness of the tire to be used in military cars. Specifically, their results showed that the desired mesh stiffness and actual stiffness were within reach, with a low stress level under a dynamic situation [50]. Xu et al. (2024) expressed the vibration of radial tires with a complicated tread pattern based on a 3D model. They utilized the model to analyze correlations between air pressure, load, and the belt angle with the sound patterns. They observed that the association between the tire frequency and the variables was a root-square relationship. Furthermore, they confirmed the simulation findings with test data and demonstrated that simulation results may give important information concerning tire noise reduction [51]. Lastly, Saisaengtham et al. (2024) investigated the relationship between tire deformation, contact patch air volume, and air-pumping noise. With FEM, they determined the relationship between filling pressure and vertical load on air volume in the contact patch and determined that air volume in the contact patch increased under higher tire pressure and decreased under higher load, which can give a clue to an application plan for reduction in tire noise [52].

CONCLUSION

The review paper on the state of the art of FEA for tire performance gives a look into how far we've gone in our abilities to model tires and anticipate their function. An overview of the data provided from these various investigations demonstrates that:

Material Innovations: Orthotropic materials have been offered as a replacement to the steel-cord construction or as a supplement to it in order to enhance tire performance by avoiding some of the problems connected in modeling the tire structure.

Performance Optimization: FEA has been a vital component in the geometric and material property optimization of tire designs that contribute to reduced rolling resistance and fuel efficiency.

Safety and Durability: Through the use of modern modeling methods, complete safety and integrity assessments may be done under a range of loading circumstances, which is particularly significant in civilian and military applications.

The article concludes by highlighting the diverse range of potential applications for FEA in tire engineering and the potential for FEA to support future advances in tire performance and design.

FUTURE SCOPE OF WORK FOR FEA IN TIRES

The future of FEA in tire research holds several promising avenues:

Smart Materials Integration: Smart materials able to adapt to changing scenarios could improve the performance and safety of tires.

Advanced Simulation Approaches: By using more sophisticated simulation approaches, such as multi-scale modeling, the tire may be more properly defined and its reaction under complicated loading scenarios better understood.

Environmental Impact Studies: Future investigation may encompass studying the environmental impacts of tire materials and designs with the possibility of enhancing sustainability in the manufacture of tires.

Real-time monitoring: If we can build FEA models that use real-time input from the tire sensors, proactive maintenance and safety can be improved.

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