DOI 10.15302/J-SSCAE-2018.01.013

Tire Dynamics Collaborative Development Strategy

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Abstract: Tire dynamics is an important bottleneck in the autonomous development of automobiles and aircraft. This study compares the development of tire dynamics research at national and international levels. Our work indicates that there is a significant challenge in the development of tire dynamics research in China in the face of increasingly fierce international competition. Strategies and suggestions for collaborative development to characterize tire dynamics in China are proposed after analyzing tire dynamics testing, simulation, and application technology.
Keywords: tire dynamics; automobile; airplane; collaborative development; strategy

1 Introduction

Tires are indispensable parts for cars, airplanes, and even spacecraft. They are the only components that come into contact with the ground and execute the load and motion functions of a car or aircraft. Characterizing tire dynamics is an important bottleneck for independent aircraft and automobile research and development and is an internationally recognized problem [1–4].

Tire has a multi-layered structure, and the tread and road surface are always in a variable rolling contact state. Various loads from the road surface are transmitted by the complex deformation of the tread and carcass in the grounding footprint. Factors affecting the dynamic characteristics of the tire include the side angle, roll angle, and longitudinal slip ratio. When the motion track of the tire on the road has a large curvature, there is a large turning rate input. In addition, vertical load, rolling speed, tire pressure, road friction coefficient, road surface curvature, and temperature have significant influences on the dynamic characteristics of tire. In addition to vertical force, there are lateral force, longitudinal force, tilting torque, rolling resistance torque, and returning torque between the tire and road surface, and these forces may influence each other because of tire deformation. The contact, adhesion, slippage, and detachment between the tread unit and road surface also cause strong nonlinearity in the dynamic characteristics of tire. Therefore, the dynamic characteristics of tire describe the complex mechanical relationship between multiple inputs and multiple outputs of a coupled nonlinear system. Mastering the core data, technology, theory, and concepts of tire dynamics requires complete understanding of the characteristics and data, advanced models, and specific applications related to tire dynamics.

2 Development history of tire dynamics research nationally and internationally

2.1 Foreign tire dynamics research

In the United States, Germany, and the Netherlands, tire dynamics research began in the 1930s. The tire models Fiala, UA, and Magic Formula (MF) were developed. As model accuracy improved, the application scope extended from a single working condition to composite conditions with four-dimensional inputs, including side slip and longitudinal slip. The MF tire model proposed by Professor Pacejka of TU Delft in the Netherlands in the mid-1980s can obtain model parameters describing mechanical characteristics of tires from tire characteristic test data through parameter identification technology. The MF tire model has been widely applied in automobile and aircraft ground dynamics

Received date: January 25, 2018; **Revised date:** February 9, 2018
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Funding program: CAE Advisory Project “Research on Tire Dynamics Collaborative Development Strategy” (2016-XY-05)
Chinese version: Strategic Study of CAE 2018, 20(1): 091–096
Cited item: Guo Konghui et al. Tire Dynamics Collaborative Development Strategy. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2018.01.013

research. Concurrently, tire dynamics testing and modeling techniques for non-horizontal pavements have also been developed rapidly including FTire, SWIFT, and CDTire [1].

Practical experience shows that the main driving force for the development of theory and applied technology is the advancement of testing technology. At present, the Flat–Trac series of six-component force test rigs developed by the American MTS Systems Corporation has been widely used in the automobile tire dynamics testing field. In comparison, for aviation tire dynamics testing technology, the US Air Force began constructing an aircraft performance testing laboratory at the Wright-Patterson Air Force Base (WPAFB) in Ohio and US Air Force Landing Gear System Center of Excellence (LGSCE) in the late 1920s and early 1930s. For example, there is a six-component force dynamometer for aviation tires with a drum diameter of 3.04 m (120 in). The speed of the drum, vertical load of the tire, side angle, and roll angle can be dynamically controlled and the coupled nonlinear six-component force characteristics of the tire under complex motion conditions can be accurately measured. There is also a six-component force dynamometer for aviation tires with an inner drum diameter of 4.2672 m (168 in). Using an inner drum surface as the simulation pavement, actual pavement conditions can be simulated by inserting different pavement materials. In addition to controlling the drum speed, tire vertical load, side angle and roll angle, the braking torque or brake slip ratio of the tire can also be controlled, which allows the six-component force characteristics of the tire in complex coupling state to be accurately measured. A flat-type aviation tire six-component force dynamometer can comprehensively test tire dynamic and static mechanical properties. The tested tire is mounted on a positioning frame, which sets the side angle and roll angle of the tire, and provides vertical loading and braking. The flat plate used for simulating road surfaces can move longitudinally to drive the tire to rotate and can be composed of different pavement materials to meet test requirements. Under this configuration, the coupled six-component force characteristics of the tire under complex motion condition can be accurately measured. This device is mainly used for measuring the rolling relaxation length of the aviation tire, cornering stiffness, lateral stiffness of the carcass, back positive stiffness, and torsional stiffness of the carcass [5,6].

The National Aeronautics and Space Administration (NASA) Langley Research Center established the Aircraft Landing Dynamics Facility (ALDF) in 1956. It is extremely large, with a test runway length of 853 m (2800 ft) that has been continuously upgraded. Because aviation tire dynamics have always been the focus of the center’s research, aviation tire hydroplaning and tire pavement friction and wear are well-studied. In 1960, the NASA Technical Report R-64 (Mechanical Properties of Pneumatic Tires with Special Reference to Modern Aircraft Tires) was released, which was based on a large number of test studies. The main objective of the report was to study the main parameters affecting the mechanical properties of aviation tires, which can be expressed by a quantitative formula [7]. In January 1998, the NASA Langley Research Center established a landing gear studio. The staff consisted of landing gear and tire manufacturers, civil aviation, general aviation, the Federal Aviation Administration (FAA), and WPAFB. The consensus was that the dynamic behavior of the landing gear shimmy and brake vibration can be predicted by simulation as long as accurate tire mechanical properties are used as inputs to the model [8]. The studio requested that the NASA Technical Report R-64 be updated to cover the dynamics characteristics of radial tires and high-grade bias tires, and substantial tire characterization tests were launched comprehensively in the summer of 1999, with some results released subsequently [9]. Concurrent with the development of the aviation tire mechanical performance testing equipment, simulation applications based on test results were being conducted. In 2000, under the guidance of Professor Pacejka, Besselink systematically launched research on the shimmy of the main landing gear based on previous research. The research group found that simulations of aircraft ground dynamics can locate the shimmy problem in the early stage of landing gear design, resulting in improvements. The current multibody dynamics simulation software combined with high-precision tire models can accurately analyze the aircraft shimmy [10].

Based on this review, it is clear that foreign countries have systematically developed testing, simulation and application technology for automobile and aviation tire dynamics that supports the research and development of high-performance automobiles and aircraft.

2.2 Domestic tire dynamics research

Tire dynamics research in China was driven by the high-speed stability problem of the Red Flag (Hongqi) car in the 1960s. Due to the lack of experimental support, initial progress was slow. In 1984, with the successful development of the QY7329 tire test rig, tire dynamics tests were finally possible and research in this area rapidly advanced. Over the years, based on the technical difficulties of high-precision full working conditions and considering the actual needs of China’s automobile development, innovations in the theory, methods, equipment, and application technology of automobile tire dynamics was completed. First, a unified modeling theory of tire dynamics was established and a new unsteady modeling method for coupled transfer matrix was proposed. A unified model with a multivariate dimensionless combination was established using the normalized transformation of the tire multi-dimensional input, which solves the theoretical modeling problem of high-precision full working conditions. Second, the road surface dynamic friction coefficient separation and insertion method was created, integrating the full working conditions of the theoretical model and advantages of boundary high precision and local high precision empirical modeling. This established a semi-physical UniTire model with high precision and complete practical working conditions. Third, a composite four-link motion decoupling tire test bench and micro-environment box all-weather, full-channel simulated tread friction characteristics test bench were developed to test tire dynamics under full working conditions with high precision. Fourth, the UniTire model parameter classification and step-by-step high precision identification method was proposed, resulting in three versions of the UniTire model application software and parameter identification tool software for different design stages of the car. This provided high-precision tire models for automobile development [11–14].

However, research on aviation tire dynamics has lagged. In October 1989, the Chengdu Aircraft Development Department compiled the Chinese version of the book "Mechanical Characteristics of Modern Aviation Tires," which became one of the most important reference materials for aircraft development in China. The lack of test data for tire dynamics has seriously hindered research on aviation tire dynamics in China. All of the limited application research has used static test data and empirical formulas from foreign literature to roughly estimate the mechanical properties of aviation tires in the design stage of landing gear, which is later verified with landing gear system tests. System test failures due to tire dynamics are difficult to explain in the absence of sufficient data. In 2011, Jilin University and the China Aviation Industry Corporation Xi'an Aircraft Design Institute jointly launched the "LMS Advanced Tire Model Library Technology Development," and applied the nationally-developed UniTire model to simulations for aircraft development. This addition has already shown significant advantages compared to the general tire model in the common analysis software, and significantly improved the accuracy of the simulation analysis results. The simulation results are in general agreement with aircraft ground turning tests and front landing gear vibration tests, which indicates the significant potential for further applications.

Recent years have been a golden period for the development of China's aviation industry as represented by the large number of in-service and ongoing research projects. However, the lack of observational data on the six-component force of aviation tires has resulted in a deviation between simulation analysis at the design stage and implementation in practice. Problems are often found, such as the shimmy in the landing gear system in the test phase. In severe cases, design changes are required, resulting in problems, such as delays in the time cycle, increase in test costs, and inability to effectively guarantee design quality. In the future, international competition faced by the automobile and aircraft industries will become increasingly fierce, and the development of tire dynamics research in China still has considerable challenges.

3 China's collaborative development strategy for tire dynamics research

Tire dynamics research covers the theory and technology of testing, simulation, and application. It includes both automobile and aviation tire dynamics. Therefore, the same theory, technology, and methods are the important foundation for the collaborative development of automobile and aviation tire dynamics research.

3.1 Collaborative development strategy for testing technology

China's tire dynamics testing technology has the following characteristics.

(1) China's automobile tire dynamics testing technology and aviation tire dynamics testing technology show an unbalanced development trend. Compared to automobile tire dynamics testing technology, China's aviation tire dynamics testing technology remains in its initial phase and is in urgent need of development.

(2) The development of heavy-duty automobile tire dynamics testing technology and passenger car tire dynamics testing technology is disparate, with clear limitations in heavy-duty vehicle tire dynamics testing technology.

(3) Passenger vehicle tire dynamics test equipment has been invested in at the expense of other technologies. Thirteen MTS Flat-Trac test rigs were purchased in China from 2004 to 2007, but relevant test specifications and test technology research have not been conducted.

(4) Compared to the rapid development of China's aviation industry, the development of aviation tire dynamics test equipment has lagged significantly; there is no available aviation tire dynamics test equipment in China.

(5) The theory and application research of tire dynamics testing technology has yet to be conducted in detail. Test equipment is a hardware platform for developing test technology, but the test equipment does not represent the test technology. It is necessary to clearly understand tire dynamics theory before research on test technology can be performed in a targeted manner.

(6) There are still many gaps in tire dynamics testing technology related to standards and specifications. Compared to the perfected tire dynamics test standard system in the United States and Europe, the development of China's tire dynamics standards has just begun.

(7) Talented individuals with relevant experience in dynamics testing technology are rare. There is less professional training and a lack of systematic planning for cultivating new talent.

The biggest problem reflected in these characteristics is unbalanced development. To solve this problem, China's tire dynamics testing technology needs to be the subject of collaborative development represented by the following synergistic relationships.

(1) Between enterprises and the state in investing in test technology development. Development of test technology requires the necessary funds to be used for constructing test equipment. According to the current status of China's test equipment, companies have invested heavily in high-production passenger car tire test equipment. To address the deficiencies in aviation tire dynamics test equipment, with higher technical content and greater investment needs, the state needs to invest more funds to support test equipment construction.

(2) Between purchasing foreign technology and developing independent technology. Objectively, there is a gap between the overall level of tire dynamics research in China and foreign countries. However, China does have unique technology in tire dynamics testing technology. For example, the principle of the composite slip test with a constant tire imprinting center is our own patented technology and superior to current MTS test technology. Therefore, we must incorporate foreign advanced technology while also developing China's own testing technology, especially for the aviation tire dynamics test bench. This combination will establish a basic technical system to support the rapid development of aviation tires and aircraft.

(3) Between test and simulation technology. Simulation technology can be viewed as a type of testing technology. It is an effective extension of existing testing technology, and the close combination of testing and simulation technology can build a more comprehensive tire dynamics testing system. For example, the simulated road surface that meets the requirements for high-speed heavy-duty testing of aviation tires is the drum surface, but the curvature of the drum has a non-negligible effect on the test results. Large-diameter drums are expensive to manufacture and cannot eliminate the influence of curvature, but we can achieve the goal of testing the dynamic characteristics of aviation tires with small-diameter drums when combined with simulation technology. The relevant technologies for this relationship are patented.

(4) Between aviation and automobile tire testing technologies. All tires are inflated and roll on the road. Both aviation and automobile tires have the same dynamic mechanism. The only differences are the specific conditions, such as load, speed, and road surface. Therefore, a set of high-level testing equipment can be built that can both meet the needs of aviation tire testing and overcome the shortcomings of current automobile tire dynamics testing.

(5) Between test equipment and key component development. One difficulty in developing tire dynamics testing equipment lies in developing key components. For example, a large-range six-component force sensor is required in heavy-duty tire dynamics testing, which relies on foreign imports to China. Huge monetary investments are required to purchase large numbers of this type of sensor, which does not help China master the relevant technology. Therefore, we need to invest resources in research and development of key components to ensure the continuous development of tire dynamics testing technology.

(6) Between test equipment and standard specification development. Standard specifications represent the technical level of a field and requires systematic and in-depth research. If the testing technology is mastered, it is easy to formulate standard specifications that meet the development needs in China. Otherwise, copying foreign standards may restrict the development of tire dynamics testing technology in China.

(7) Between technical research and talent cultivation. Tire dynamics is the basis for vehicle dynamics. Both theoretical and experimental research is very challenging in these disciplines. Therefore, there are few teams focusing on tire dynamics research worldwide and the number of talented researchers trained every year is very limited. However, the demand for professionals in dynamic testing technology is very urgent. Therefore, it is necessary to build a communication platform to train technicians who can meet the development needs of China's tire dynamics technology.

3.2 Collaborative development strategy for simulation technology

International tire dynamics research is best represented by Professor Pacejka of the Netherlands, who has conducted very systematic and in-depth theoretical research. His engineering applications, based on empirical measurements, remain dominant. This pure experience method is the mainstream method for establishing a tire model, and is based on observations from a large number of tire test data to identify characteristic mathematical formulas and use parameter identification technology to establish a pure empirical description between the output and input variables for tire dynamics. The MF tire model proposed by Professor Pacejka is the most representative. The theoretical model adopts the specificity hypothesis, and the application scope for working conditions is small and the precision is not high.

Domestically, tire dynamics research is best represented by Professor Guo, whose research is based on theory. The internal relationship behind the complex tire dynamics is clarified by establishing a theoretical model with full working conditions. The semi-physical UniTire model draws on the advantages of empirical modeling but is based on theoretical model guidance.

Therefore, the development of China's tire dynamics simulation technology should fully use existing theoretical work to meet the objective of rapid development in the automobile and aerospace industries, which are described by the following synergistic relationships.

(1) Between the development of automobile and aviation tire dynamics simulation technology. Both automobile and aviation tires are the only parts of the vehicles that come into contact with the ground and tire mechanical properties are crucial for the development of both automobiles and aircraft. However, for various reasons, the development of automobile and aviation

tire dynamics simulation technologies have been unbalanced. Currently, using nonlinear unsteady tire models in automobile dynamics simulations is a common approach, but the latest tire model technology has not been widely used in aircraft ground dynamics simulations.

(2) Between simulation and testing technologies. The application of simulation technology can significantly shorten the development cycle and reduce development costs. At present, developing automobiles without simulation technology is challenging. Furthermore, developing simulation technology is inseparable from the support from testing technology. Vehicle tire dynamics testing technology is basically sound, but China's aviation tire dynamics testing technology is extremely limited and urgently needs development.

(3) Between simulation technology and application technology. The purpose of a simulation is to implement a design, and the requirements of this implementation or application will guide the development direction of simulation technology. Different application problems have different tire dynamics model requirements; therefore, software tools used in the application of the tire dynamics model should be developed.

(4) Between theoretical research and empirical modeling methods. The tire structure is complex and working conditions vary. The vibration, noise, and rim characteristics of the tire should be taken into consideration. The description of the dynamic characteristics has always been a difficult problem in the field of vehicle dynamics research. Existing work shows that purely theoretical or purely empirical tire dynamics models have problems in application. Instead, semi-physical or semi-empirical models are the current direction of tire dynamics simulation technology development.

3.3 Collaborative development strategy for application technology

Relying on the commercial software platform, foreign tire dynamics application technology has been popularized, and the following problems still exist in the development of China's tire dynamics application technology.

(1) Medium and high frequency tire models in China are not widely applied. Only some units in China use medium and high frequency models, such as FTire and SWIFT. Due to the complexity of the model and limitations in user capabilities, there are many incomprehensible and unverifiable formulas, which affects the in-depth application of the FTire and SWIFT models.

(2) Many advanced models in foreign countries have achieved a leading position in the automobile tire industry and achieved docking and embedding with dynamic software, which has resulted in substantial success with aviation tires. China's aviation tire dynamics modeling has not been detailed or comprehensive enough even using simplified linear models when solving practical problems, which has resulting in simulations with low reliability.

(3) Although China has introduced tire models, such as PAC2002 and FTire, only models for civil vehicle tires have been accurately built for some technical reasons. Due to the difference between civil and military tires, and between aviation and automobile tires, military and aviation tire development has clearly lagged behind the development of civil tire mechanics. For aviation and military tires, it is necessary to learn from foreign technological achievements and incorporate innovations to broaden tire dynamics applications. In addition, research on tire design methods based on tire dynamics applications has been insufficient.

To solve these problems, it is necessary to coordinate the development of China's tire dynamics application technology, with a focus on the following synergistic relationships.

(1) The development of basic databases and process specifications. It is necessary to strengthen the construction of the basic resource library for simulations and adhere to the principle 'Focus on my purpose'. We should comprehensively use combined virtual and real methods to construct a simulation basic resource library available for engineering based on historical simulation and accumulated experimental data; introduce the maturity management method to simulation model management; and establish a multi-level, multi-precision, multi-scale simulation model management method and industry modeling specifications to establish a simulation credibility evaluation system for automobile, aircraft, and tire design.

(2) The development of tire model interface technology for different design stages. At different stages of automobile or aircraft development, the application problems are different and tire models with different degrees of complexity are required. Therefore, developing a series of tire models based on the interface specification of the dynamic simulation platform is an effective means to meet the application requirements.

(3) The development of independent model application technology and imported model application technology. Due to the complexity of tire models, a strong technical background is needed in the application. To facilitate the application of the tire model, it is necessary to develop software tools for parameter identification and adjust the models; various tire models can be correctly applied using appropriate software tools.

4 Suggestions to accelerate the collaborative development of tire dynamics research in China

4.1 Objectives of the collaborative development of aviation tire dynamics and automobile tire dynamics to achieve complementary advantages and common development

The automobile industry is the pillar industry of China's national economy, and the aviation industry is the pillar of highend manufacturing. Tire dynamics includes both automobile and aviation tire dynamics. The similar theory, technology and methods are an important foundation of the synergistic development between automobile and aviation tire dynamics, and only collaborative development can fully use existing technologies, create complementary advantages, break through foreign technical barriers, and support the rapid development of China's joint automobile and aviation industries under current conditions. Tire dynamics testing technology is the basis for simulation technology, and simulation technology is the basis for application technology. Tire dynamics testing, simulation, and application technologies should be used as the starting point to realize the collaborative development of tire dynamics research.

4.2 Using the 'coupling nonlinear six component force testing equipment for aviation tire' as a breakthrough to meet the needs of high-performance aircraft development

The aviation tire is an important component of the aircraft landing gear system. Its rolling mechanical properties, i.e., six-component force characteristics, directly affect the movement characteristics of the aircraft during take-off, landing, braking, turning, and taxiing phases and are directly related to aircraft safety. The six-component force characteristics are very important basic data for designing aircraft, especially high-performance aircraft. China is still using the data guidance manual dating back to the 1950s. However, the current tire technology has undergone qualitative changes compared to technology in the 1950s, and the performance of aircraft has also made a qualitative leap. It is non-rigorous and potentially dangerous to continue using data from that time, and special test equipment for measuring the six-component force characteristics of aviation tires is needed.

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