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Intelligent Tire Systems

Springer

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Intelligent Tire Systems

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ISSN 2576-8107 ISSN 2576-8131 (electronic)
Synthesis Lectures on Advances in Automotive Technology
ISBN 978-3-031-10267-7 ISBN 978-3-031-10268-4 (eBook)
https://doi.org/10.1007/978-3-031-10268-4

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Vehicle performance is largely controlled by the tire dynamic characteristics mediated by forces and moments generated at the tire-road contact patch. The tire may undergo deformations that increase the longitudinal and lateral forces within the contact patch. Therefore, it is crucial to develop a model for the accurate prediction of tire characteristics, as this will enable optimization of the overall performance of vehicles. During the past decades, extensive research has been conducted to identify new strategies for tire measurement and modeling vehicle dynamics analysis.

The development of autonomous vehicles (AVs), electric vehicles (EVs), shared fleets, and connected vehicles has further revolutionized interdisciplinary research on vehicle and tire systems. The performance and reliability of vehicle active safety and advanced driver assistance systems (ADASs) are primarily influenced by the tire force capacity, which cannot be measured. The need for a high active safety and optimized ADAS is particularly crucial for automated driving systems (ADS) to guarantee passenger safety in intelligent transportation settings. Therefore, the establishment of online measurement or estimation tools for tire states, especially for autonomous vehicles, is critical.

The concept of intelligent tires has drawn strong interest from researchers with regard to the prediction and estimation of tire states for autonomous driving settings, advanced vehicle control, and artificial intelligence. An intelligent tire system is defined as a system that can intelligently extract and send valuable information about tire and road conditions to the vehicles' Electronic Control Unit (ECU). Thus, it is crucial to develop novel sensing systems and estimation techniques for tires for real-world applications.

This book consists of 6 chapters. In Chap. 1, the basic concepts and features of intelligent tire systems are introduced. Promising application fields and benefits from the systems are also discussed.

In Chap. 2, the tire dynamics is presented through tire modeling. The existing tire models developed with different approaches are briefly reviewed. The key modeling considerations, such as the elasticity of the carcass, friction characteristics, and pressure distribution, are analyzed and modeled with different complexities. Physical models from simple to refined and the UniTire semiempirical model are derived.

In Chap. 3, various types of sensors for tire condition monitoring are provided. For different features of tires to be monitored in working conditions, sensors can be chosen according to their working principles and characteristics. To make the sensor maintenance-free, i.e., without changing the battery in its life cycle, the energy harvesting techniques are briefly introduced, which can be used as a power source for the sensors. Additionally, they have the potential to be used as sensors themselves.

In Chap. 4, the methods and the process of tire force prediction utilizing acceleration signals are discussed. Extensive analysis of the signal under various working conditions is performed in both the frequency and the time domains. The data preprocessing and contact patch identification methods used in this book are discussed in detail. Both physical-model-based and machine learning methods are exploited to acquire satisfactory force prediction results.

In Chap. 5, the kinematic states of the tire, namely, the slip ratio and the slip angle, are predicted using acceleration information. The effects of the slip angle and the slip ratio on the acceleration are analyzed. After that, the prediction of the slip ratio and the slip angle are performed using both the physical-model-based approach and the machine learning method.

In Chap. 6, the estimation methods of the tire-road friction coefficient are explained. The tire states required by the estimation methods are the predicted values from the intelligent tire system developed in previous chapters. The pneumatic trail, which is difficult to obtain with traditional on-board sensors but easy with the intelligent tire system, is a promising indicator for the tire slip state description. To obtain the pneumatic trail, the aligning moment is predicted by a trained machine learning model. Finally, both the force-based methods and the pneumatic-trail-based friction estimation approaches are examined.

This book is recommended for graduate or senior-level undergraduate course. Depending on the background of the students in different disciplines, such as mechanical and automotive engineering, course instructors have the flexibility to choose appropriate chapters. This book is also an in-depth source and a comprehensive reference in the tire and automotive industry for researchers, engineers, and practitioners.

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March 2022

Acknowledgments

Most of the work described in this book has been carried out at the State Key Laboratory of Automotive Simulation and Control (ASCL), Jilin University, Changchun, China, and also the Department of Mechanical and Mechatronics Engineering, University of Waterloo, Canada. We are grateful to all members of the Tire and Vehicle Dynamics Research group as well as the Mechatronic Vehicle Systems group, especially Dr. Jianfeng Zhou and Mr. Zepeng Tang, who made great contributions to the slip ratio sections and preparation work of this book. In addition, we would like to express our sincere gratitude to Prof. Yanjun Huang and Prof. Bruno Henrique Groenner Barbosa, who provided their valuable suggestions for tire slip angle estimation and advanced machine learning techniques, respectively.

We would also like to express our sincere thanks to the National Natural Science Foundation of China (Nos. 51875236 and 61790561) for supporting authors' research, and the China Automotive Technology and Research Center Co., Ltd (CATARC) for providing the advanced tire testing facilities during our research. In addition, we would like to acknowledge the efforts and assistance of the staff of Springer Nature publishers, especially Paul Petralia and Boopalan Renu. Last but not least, we thank our families, especially our wives, for their unconditional support and absolute understanding during the writing of this book.

March 2022

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Abstract

Estimating of tire properties is urgently needed for the development of an effective and accurate vehicle control strategy. Several modeling and estimation techniques have been proposed for tire and road interaction forces. They have shown the capability of predicting tire forces to some extent; however, they malfunction in harsh driving maneuvers. In addition, tire wear and dependency on road surface conditions limit their capabilities in the precise estimation of tire dynamic parameters, including road friction. Tire force measurement devices can only be exploited for vehicle testing because of the cost, which is on the order of tens of thousands of dollars. Tire pressure-monitoring systems have been mandated, and they are the only available measurement devices in newer and higher end vehicles, but there is no sensory system available to provide tire forces, moments, and road frictions. Recently, the idea of an intelligent tire, which is in fact a self-sufficient sensing system, has attracted the attention of the tire and the automotive industries with the aim of measuring tire dynamic parameters and road surface frictions online. As the industry moves with a brisk pace towards autonomous driving, intelligent tires with the capability of online tire dynamics and road surface friction prediction will play a vital role in terms of safety, reliability, and public confidence in automated driving.

This book aims to show how intelligent tires can boost our understanding of tire dynamics. In addition, we discuss the important role of intelligent tires in future autonomous and connected driving. The Chap. 1 of the book presents the full structure of an intelligent tire and the necessary steps to furnish the current tires with intelligence. In the Chap. 2, an introduction to the fundamentals of tire modeling is presented. Different potential sensing systems for tire monitoring are illustrated in the Chap. 3. Chapter 4 describes the signal processing and estimation techniques, including the analytical methods and also machine learning techniques, for finding tire forces based on experimental data. The focus of Chap. 5 is on the estimation techniques of the tire slip angle and slip ratio, which are important parameters for vehicle dynamics control and stability assessment. The last chapter presents the applications of intelligent tires for the prediction of tire aligning moments, pneumatic trails, and road friction.

Keywords Intelligent tire · Tire characteristics · Machine learning · Sensing systems · Tire force estimation · Vehicle system dynamics

Contents

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Introduction to Intelligent Tires

1

1.1 Introduction

Tires are one of the most essential components in vehicle dynamics in terms of safety for drivers and passengers. Accordingly, it is important to develop a tire condition monitoring system (TCMS), such as tire pressure monitoring, to improve road traffic safety and reduce disastrous accidents due to tire failure. Generally, a TCMS is used for online observations of tire health and conditions in terms of pressure, wear, forces, moment and friction coefficient. Integrating a TCMS with vehicle sensory systems and active control provides a warning system for the vehicle, which can inform the driver if any unsafe change has occurred in the measured values related to tire systems. In addition, this monitoring system plays an important role in vehicle stability adjustment, especially when the vehicle is on its limits in terms of available tire forces on each corner. It should be noted that a TCMS is also very important for preventing deflated and flat tires. We know that flat tires are considered to be one of the main reasons behind extra fuel consumption, noise emissions, extreme tire wear, tire lifetime reduction, CO_2 emissions and higher rolling resistance.

Technically, a tire with a TCMS is called an intelligent tire, as it can intelligently react to different interacting conditions between the tire and the road and the unsafe changes in the extracted data through embedded sensory systems. The successful development of an intelligent tire requires the combination of different fields, including artificial intelligence for translating the raw data to meaningful information for vehicle control systems, self-powered sensing for online measurement and energy harvesting purposes, and cyber-secure data transmission to avoid data breaches. Figure 1.1 shows the main branches needed for the development of an intelligent tire. As depicted by Fig. 1.1, considering vehicle and tire dynamics as the core focus of an intelligent tire, it is necessary to have a multidisciplinary team of researchers with backgrounds in vehicle and tire dynamics, computer science, telecommunications and cyber-security, mechatronics, and material sciences for the full development of an intelligent tire with all required features.

N. Xu et al., *Intelligent Tire Systems*, Synthesis Lectures on Advances
in Automotive Technology, https://doi.org/10.1007/978-3-031-10268-4_1

Fig. 1.1 The multidisciplinary nature of an intelligent tire

1.2 Advantages of Intelligent Tires

During the last two decades, estimation methods have shown the capability of estimating tire dynamics parameters to some extent; however, they usually fail to provide fully reliable results when there are changes in road conditions and tire parameters due to wear and temperature. In general, estimation techniques malfunction when they deal with slightly convoluted driving conditions. Therefore, integrated vehicle control, which depends on an accurate estimation of tire parameters, fails to provide the required actuation related to that specific driving condition. This is where a tire condition monitoring system, and more generally, intelligent tires, can improve tire dynamics parameter online estimation and vehicle control performance. This is one of the most important advantages of using intelligent tires in future vehicles [1, 2].

Determining tire dynamics parameters is one of the many features that can be provided by intelligent tires. The tires of the future can play a crucial role in preventative maintenance by providing online information about abnormal temperature increases in tires and the detection of small punctures. It is known that an abrupt tire temperature increase is an indication of a tire blowout, which can be identified by embedded sensory systems in intelligent tires. Having a warning system for small punctures prevents further damage to the tire, which reduces the risk of accidents. These two features drastically improve vehicle safety.

Intelligent tires can also lead to a reduction in CO_2 emissions. Based on EU-15 estimation, the simple use of a tire pressure monitoring system (TPMS) reduces CO_2 emissions by 9.6 million tons per year. This is clearly related to the fuel consumption of the vehicle, as maintaining proper tire pressure will result in an efficient rolling resistance, as well as a tire grip. At the same time, proper tire pressure plays an important role in vehicle safety, as it directly affects vehicle handling and stability. In addition, it is expected that intelligent tire technology will have the capability of adjusting tire pressure automatically and autonomously.

Another important application of intelligent tires is the online estimation of road friction, as well as road classification. In fact, the ultimate aim in vehicle dynamics state and parameter

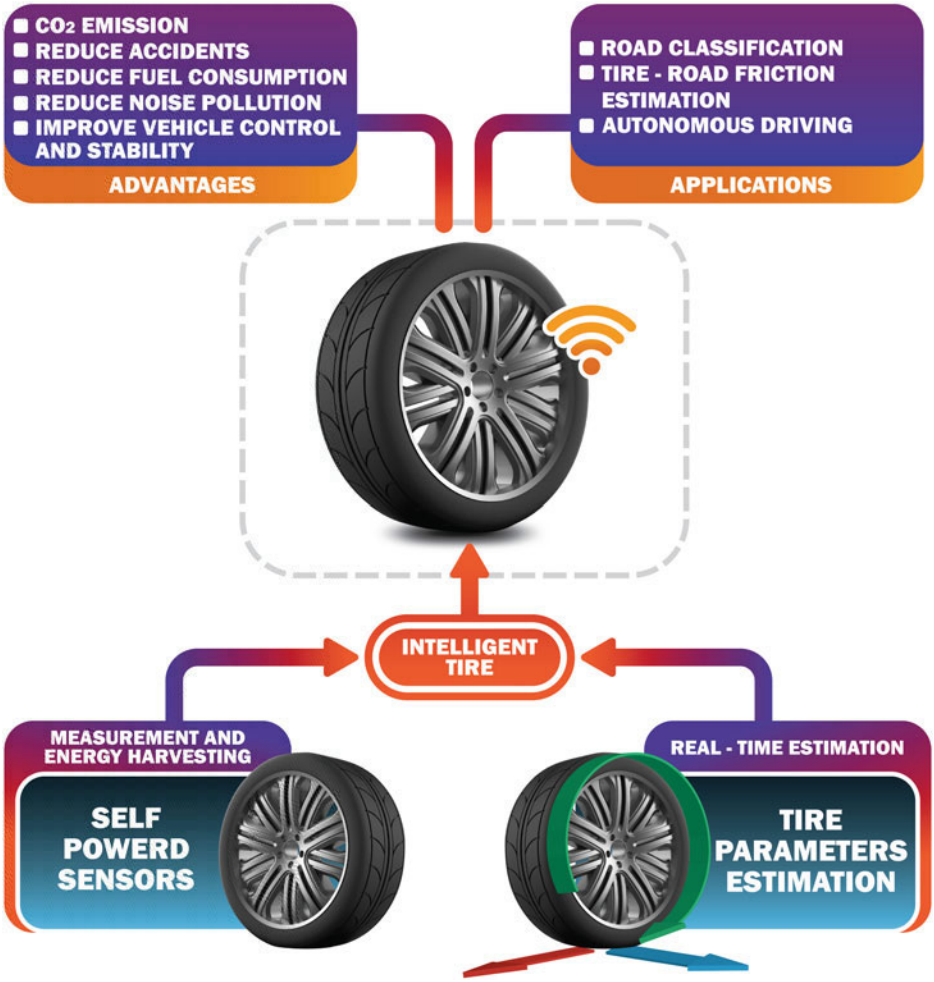

Fig. 1.2 Applications and advantages of intelligent tires [3]

estimation is determining road friction, and apparently, intelligent tires can be a game changer in this context. Figure 1.2 represents different applications and advantages of intelligent tires.

1.3 Evolution and Prospective Research on Intelligent Tires

During the last two decades, several works have been performed in the areas of tire dynamics and sensing systems ranging from the development of complex mathematical models and estimation techniques to novel devices with the aim of self-powered sensing. The utilization of self-powered sensing in intelligent tires has recently gained traction as a new method for energy harvesting, resulting in smaller, reliable and more efficient devices. In fact, furnishing tires with self-powered sensing systems can reduce the need for battery replacement in integrated sensors and accordingly improve the overall safety of vehicles. The development of such devices can only be actualized using novel materials. Thus, one of the main branches of research on intelligent tires will be the use of novel materials to realize a TCMS furnished by self-powered sensing systems, and therefore the electrification of tires.

Similar to future vehicles, intelligent tires will also be autonomous, meaning that they will have the capability to monitor and adapt their own pressure automatically. This feature increases road safety, prevents accidents due to tire failure, and enhances tire lifetime. This feature can be added to tires with the combination of advanced knowledge of pneumatics, mechatronics, and artificial intelligence.

Considering the connectivity and the signal transmission between tires and vehicle control systems, as well as cloud computing, they should also be connected similarly to future vehicles. This is an important area of research that should be fully investigated. In this book, we mainly focus on three aspects of intelligent tire systems, including tire dynamics and related mathematical models, sensing and energy harvesting approaches, and machine learning techniques that can be used for the online estimation of tire parameters. We discuss the structure of the book in the next section.

1.4 Structure of the Book

This book includes 6 chapters in which we present different aspects of intelligent tire systems. The first chapter provides a brief review of the concept of intelligent tire systems, their advantages, and their applications. In addition, the evolution of intelligence during the last two decades is discussed.

Chapter 2 presents a comprehensive literature review considering the modeling approaches of tire dynamics with the aim of providing readers with a full picture of the existing tire models. The chapter covers a simplified brush model with a rigid carcass by discussing tire modeling basics, pure slip conditions, and longitudinal and lateral combined slip conditions. In addition, we present a tire theoretical model considering flexible carcass. The very last part of the chapter provides a detailed discussion of the UniTire semiempirical model.

Chapter 3 discusses different sensing methodologies used for the development of intelligent tire systems. It covers different forms of sensing approaches, including optical, capacitive, optical fiber, surface acoustic wave, ultrasonic, and MEMS-based accelerometers.

Chapter 4 presents the instrumentation procedure for developing intelligent tire technology using accelerometers. The experimental setup and procedure are also discussed for extracting the data from the accelerometer attached to the inner liner of the tire. A detailed frequency and time domain analysis are presented to evaluate accelerometer signals under different loading conditions. A physical model-based tire force estimation is also developed