

A Parametric Study on Wheel Flat-induced Impact Responses for Wheel Condition Monitoring

Master Thesis

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by

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Preface

After two years of study, my master’s journey at Delft University of Technology has come to an end. Along the way, I experienced both the exhilaration of achievement and the frustration of setbacks. Through it all, one feeling has remained constant—gratitude. I am deeply thankful to everyone who has supported me and inspired me throughout my master’s study.

I would like to express my sincere gratitude to the chair of my assessment committee, Dr. Zhen Yang, whose guidance and support have been invaluable over the past year and beyond. From the B6-module coursework in Year 1 to my research internship in the first quarter of Year 2, Dr. Yang’s mentorship enabled me to develop a systematic understanding of railway engineering knowledge that formed a solid foundation for this master thesis. During the thesis-planning stage, Dr. Zhen Yang offered numerous constructive suggestions that proved crucial for the research that followed. Even while managing a demanding schedule, Dr. Zhen Yang consistently provided timely feedback and engaged in thoughtful discussions, ensuring I remained on the right track. I am also deeply thankful to Dr. Chunyan He, an exceptional researcher and supervisor, who lifted my confidence whenever challenges arose and guided me in overcoming them. From her, I have learned rigorous academic thinking and an enduring optimism that will benefit me for a lifetime.

I am also sincerely grateful to Dr. Alfredo Núñez and Dr. Kumar Anupam. As members of my assessment committee, they attended every important meeting and offered clear professional guidance that sharpened the quality of this thesis. Their questions drew my attention to details I had missed and helped me strengthen my analysis. Before the thesis began, I took several transport infrastructure courses taught by them, and the knowledge and enthusiasm they shared broadened my understanding of the field.

Special thanks go to my classmates. They worked beside me through countless late nights. Their friendship filled my journey at TU Delft with warmth. Finally, I wish to thank my parents and my girlfriend, Ziyue Lu, for their unwavering support, encouragement, and love. They are my constant source of strength.

*Hang Gao
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Summary

Driven by technological advancements, modern railway systems are increasingly characterized by higher transport capacity and improved sustainability in response to resource constraints and climate change. At present, wheel–rail contact, as the dominant technical approach for railway transportation, serves to guide the train and provide the necessary traction and braking forces. However, this contact is susceptible to defects such as wheel flats, which can cause impact vibrations and noise, and pose safety risks. To effectively detect wheel flats, axle box acceleration (ABA) measurements hold great potential, as it has been widely adopted to monitor track structures and interface deterioration. This study is conducted to develop a reliable 3D finite element (FE) model to simulate wheel flat-induced impacts, and to investigate the effects of the rolling speed and flat parameters on the impact force and ABA responses.

To achieve the research objectives, a 3D FE model with a flat was developed based on the lab test data from V-Track. The finite element analysis was conducted through an implicit–explicit sequential method, and the developed FE model was validated against experimental measurements. With the validated model, a parametric study was conducted to study the effects of wheel rolling speed, flat length, and flat development stage on the impact force and ABA responses, with the latter two parameters investigated by adjusting the discretized tread profiles in the flat region. For all simulated and measured signals, time–frequency features were obtained using Continuous Wavelet Transform and Synchrosqueezed Wavelet Transform. The resulting wavelet power spectra can effectively capture localized energy variations induced by the wheel flat.

The results demonstrate that flat-induced wheel–rail impact force increases non-linearly with wheel rolling speed, and the correlation between the flat length and the impact force is not consistently positive. Moreover, the wear development of the flat leads to a noticeable reduction in impact force at low speeds. The ABA responses are influenced by a combination of factors, including speed, wavelength, and flat-related wheel and track modes. The conclusions and recommendations presented at the end of the thesis highlight the need for a more comprehensive study that considers a broader range of flat geometric parameters to support the development of flat monitoring and the formulation of ABA-based wheel assessment rules.

Contents

Preface	i
Summary	ii
Acronyms	x
1 Introduction	1
1.1 Research Context	1
1.2 Research Problem	3
1.3 Research Objectives	3
1.4 Research Scope	3
1.5 Research Questions	4
1.6 Research Structure	4
1.7 Research Methodology	6
2 Literature Review	7
2.1 Flat-induced Wheel-rail impact contact	7
2.2 ABA Monitoring Systems	10
2.3 Regulations for Wheel Defect Assessment	14
3 Method	16
3.1 3D FE Model Establishment	16
3.1.1 V-Track Test Rig	16
3.1.2 Flat Modelling	19
3.2 Implicit-explicit Sequential Approach	25
3.3 Signal Processing	26
3.3.1 CWT and Features	26
3.3.2 SSWT and Features	27
4 Model Validation	28
5 Effects of Speed	33
5.1 Effects of Speed on Impact Force	33
5.2 Effects of Speed on ABA	36
6 Effects of Flat Length	40
6.1 Effects of Flat Length on Impact Force	40
6.2 Effects of Flat Length on ABA	42
7 Effects of Development Stage	48
7.1 Effects of Development Stage on Impact Force	48
7.2 Effects of Development Stage on ABA	50

8	Conclusions and Recommendations	54
8.1	Conclusions	54
8.2	Recommendations	56
	References	58
A	Simulation - Case 1	63
B	Simulation - Case 2	68
C	Simulation - Case 3	75
D	Simulation - Case 4	82
E	Simulation - Case 5	87

List of Figures

1.1	NS's Intercity train [2].	1
1.2	Wheel flats: (a) A severe wheel flat on a Chinese train [5]; (b) A large flat in winter conditions [6].	2
1.3	V-Track test rig and the wheel with a flat.	4
1.4	Research structure.	6
1.5	Research methodology.	6
2.1	The measured peak responses versus speed [17].	7
2.2	Test train [14].	8
2.3	Rolling wheel with a newly formed flat [3].	8
2.4	Impact force vs. train speed [18].	9
2.5	Discretized 3D wheel flats [5].	9
2.6	Wheel vertical accelerations [19].	10
2.7	The layout of the ABA system [13].	11
2.8	Prediction of short pitch corrugation (SPC) [12].	11
2.9	Wavelet transform of wheel acceleration [29].	12
2.10	The unloaded freight train with wheel flats [30].	12
2.11	Wheel-flat Kriging surrogate model [15].	13
2.12	ADSA results of the axle box [31].	13
3.1	The CAD view of V-Track [38].	17
3.2	SPC on V-Track [41].	17
3.3	The 3D FE model of V-Track [42].	18
3.4	Four identified wheel eigenmodes [43].	18
3.5	V-Track test rig with a wheel flat.	19
3.6	Discretisation of a wheel flat.	19
3.7	The scheme of 2D wheel flats.	20
3.8	The wheel profile depths taken from the central cross-section.	21
3.9	Nodal coordinate (Case 1).	22
3.10	Nodal coordinate (Case 2).	22
3.11	Nodal coordinate (Case 3).	22
3.12	Nodal coordinate (Case 4).	23
3.13	Nodal coordinate (Case 5).	23
3.14	The developed 3D FE model for flat-induced wheel-rail interactions.	24
3.15	Contact stress contour in the implicit analysis.	25
4.1	The schematic diagram of the circular track [42].	28
4.2	The measured vertical ABA at 4 km/h.	29
4.3	The measured vertical ABA at 8 km/h.	29

4.4	WPSs of the ABA signals (processed using the CWT) at 16 km/h: (a) Measured ABA; (b) Simulated ABA.	30
4.5	WPSs of the ABA signals (processed using the SSWT) at 16 km/h: (a) Measured ABA; (b) Simulated ABA.	31
4.6	LWPS of the simulated vertical ABA (processed using the SSWT) at 16 km/h.	32
5.1	Time histories of the simulated contact force at different speeds for Case 2.	34
5.2	The simulated vertical displacement at 16 km/h in Case 2.	34
5.3	The stress at the transition region (Case 2).	35
5.4	The effect of rolling speed on the impact force amplitude and the contact loss (Case 2).	35
5.5	Time histories of the simulated vertical ABA at different speeds for Case 2.	36
5.6	The effect of speeds on the RMS value and maximum amplitude of ABA (Case 2).	37
5.7	WPSs of the simulated ABA signals using the CWT for Case 2: (a) 28 km/h; (b) 32 km/h; (c) 45 km/h.	38
5.8	GWPSs of the simulated ABA signals using the CWT for Case 2: (a) 28 km/h; (b) 45 km/h.	39
6.1	Simulated contact force time histories at 100 km/h for Cases 1–3.	41
6.2	The effect of flat length on the impact force (first peak).	41
6.3	The effect of rolling speed on the impact force reported in [54].	42
6.4	Simulated vertical ABA time histories at 100 km/h for Cases 1–3.	42
6.5	The effect of flat lengths on the RMS of ABA.	43
6.6	WPSs of the simulated ABA signals using the CWT at 100 km/h with different wheel lengths: (a) Case 1 (4 mm); (b) Case 2 (6 mm); (c) Case 3 (8 mm).	44
6.7	SAWPs of the simulated ABA signals using the CWT at 100 km/h with different wheel lengths: (a) Case 1 (4 mm); (b) Case 2 (6 mm); (c) Case 3 (8 mm).	45
6.8	Key frequency bands.	46
7.1	Time histories of the simulated contact force at 100 km/h for Cases 1, 4, and 5.	49
7.2	The variations of impact force amplitude with speed induced by flats at different development stages.	50
7.3	Time histories of the simulated vertical ABA at 80 km/h for Cases 1, 4, and 5.	50
7.4	The variations of the RMS of ABA induced by flats at different development stages.	51
7.5	WPSs of the simulated ABA induced by fresh and rounded flats: (a) Case 5 (rounded) at 32 km/h; (b) Case 5 (rounded) at 45 km/h; (c) Case 1 (fresh) at 45 km/h.	52

7.6	SAWPs of the simulated ABA signals using the CWT at 100 km/h with different flat development stages: Case 1 (fresh); Case 4 (rounded); Case 5 (rounded).	53
8.1	Signature tunes of wheel flats.	55
8.2	Indicators relevant to wheel flat monitoring.	56
8.3	A preliminary framework for future research	57
A.1	The simulated ABA in Case 1 at 16 km/h.	63
A.2	The simulated ABA in Case 1 at 32 km/h.	63
A.3	The simulated ABA in Case 1 at 45 km/h.	64
A.4	The simulated ABA in Case 1 at 60 km/h.	64
A.5	The simulated ABA in Case 1 at 80 km/h.	64
A.6	The simulated ABA in Case 1 at 100 km/h.	65
A.7	The simulated contact force in Case 1 at 16 km/h.	65
A.8	The simulated contact force in Case 1 at 32 km/h.	65
A.9	The simulated contact force in Case 1 at 45 km/h.	66
A.10	The simulated contact force in Case 1 at 60 km/h.	66
A.11	The simulated contact force in Case 1 at 80 km/h.	66
A.12	The simulated contact force in Case 1 at 100 km/h.	67
B.1	The simulated ABA in Case 2 at 16 km/h.	68
B.2	The simulated ABA in Case 2 at 20 km/h.	68
B.3	The simulated ABA in Case 2 at 24 km/h.	69
B.4	The simulated ABA in Case 2 at 28 km/h.	69
B.5	The simulated ABA in Case 2 at 32 km/h.	69
B.6	The simulated ABA in Case 2 at 45 km/h.	70
B.7	The simulated ABA in Case 2 at 60 km/h.	70
B.8	The simulated ABA in Case 2 at 80 km/h.	70
B.9	The simulated ABA in Case 2 at 100 km/h.	71
B.10	The simulated contact force in Case 2 at 16 km/h.	71
B.11	The simulated contact force in Case 2 at 20 km/h.	71
B.12	The simulated contact force in Case 2 at 24 km/h.	72
B.13	The simulated contact force in Case 2 at 28 km/h.	72
B.14	The simulated contact force in Case 2 at 32 km/h.	72
B.15	The simulated contact force in Case 2 at 45 km/h.	73
B.16	The simulated contact force in Case 2 at 60 km/h.	73
B.17	The simulated contact force in Case 2 at 80 km/h.	73
B.18	The simulated contact force in Case 2 at 100 km/h.	74
C.1	The simulated ABA in Case 3 at 16 km/h.	75
C.2	The simulated ABA in Case 3 at 20 km/h.	75
C.3	The simulated ABA in Case 3 at 24 km/h.	76
C.4	The simulated ABA in Case 3 at 28 km/h.	76
C.5	The simulated ABA in Case 3 at 32 km/h.	76
C.6	The simulated ABA in Case 3 at 45 km/h.	77

C.7	The simulated ABA in Case 3 at 60 km/h.	77
C.8	The simulated ABA in Case 3 at 80 km/h.	77
C.9	The simulated ABA in Case 3 at 100 km/h.	78
C.10	The simulated contact force in Case 3 at 16 km/h.	78
C.11	The simulated contact force in Case 3 at 20 km/h.	78
C.12	The simulated contact force in Case 3 at 24 km/h.	79
C.13	The simulated contact force in Case 3 at 28 km/h.	79
C.14	The simulated contact force in Case 3 at 32 km/h.	79
C.15	The simulated contact force in Case 3 at 45 km/h.	80
C.16	The simulated contact force in Case 3 at 60 km/h.	80
C.17	The simulated contact force in Case 3 at 80 km/h.	80
C.18	The simulated contact force in Case 3 at 100 km/h.	81
D.1	The simulated ABA in Case 4 at 16 km/h.	82
D.2	The simulated ABA in Case 4 at 32 km/h.	82
D.3	The simulated ABA in Case 4 at 45 km/h.	83
D.4	The simulated ABA in Case 4 at 60 km/h.	83
D.5	The simulated ABA in Case 4 at 80 km/h.	83
D.6	The simulated ABA in Case 4 at 100 km/h.	84
D.7	The simulated contact force in Case 4 at 16 km/h.	84
D.8	The simulated contact force in Case 4 at 32 km/h.	84
D.9	The simulated contact force in Case 4 at 45 km/h.	85
D.10	The simulated contact force in Case 4 at 60 km/h.	85
D.11	The simulated contact force in Case 4 at 80 km/h.	85
D.12	The simulated contact force in Case 4 at 100 km/h.	86
E.1	The simulated ABA in Case 5 at 16 km/h.	87
E.2	The simulated ABA in Case 5 at 32 km/h.	87
E.3	The simulated ABA in Case 5 at 45 km/h.	88
E.4	The simulated ABA in Case 5 at 60 km/h.	88
E.5	The simulated ABA in Case 5 at 80 km/h.	88
E.6	The simulated ABA in Case 5 at 100 km/h.	89
E.7	The simulated contact force in Case 5 at 16 km/h.	89
E.8	The simulated contact force in Case 5 at 32 km/h.	89
E.9	The simulated contact force in Case 5 at 45 km/h.	90
E.10	The simulated contact force in Case 5 at 60 km/h.	90
E.11	The simulated contact force in Case 5 at 80 km/h.	90
E.12	The simulated contact force in Case 5 at 100 km/h.	91

List of Tables

2.1	WILD-based wheel alarm regulations in different countries [9].	14
3.1	Eigenmodes of the track structure.	18
3.2	Wheel flat geometries of the simulation cases.	21
3.3	Key parameters of the 3D FE model.	24
7.1	Wheel flats at different development stages.	48

Acronyms

Abbreviation	Definition
AAR	Association of American Railroads
RSSB	Rail Safety Standards Board
FE	Finite Element
ABA	Axle Box Acceleration
IRJ	Insulation Rail Joint
RCF	Rolling Contact Fatigue
RMS	Root Mean Square
ADSA	Angular Domain Synchronous Averaging
SPC	Short Pitch Corrugation
OOR	Out-of-round
WILD	Wheel Impact Load Detector
CWT	Continuous Wavelet Transform
WPS	Wavelet Power Spectrum
GWPS	Global Wavelet Power Spectrum
SAWP	Scale Averaged Wavelet Power
SSWT	Synchrosqueezed Wavelet Transform
LWPS	Local Wavelet Power Spectrum

1

Introduction

1.1. Research Context

Railways, as a cost-effective and reliable mode of transportation, enable high-capacity, long-distance passenger and freight transport. Regions and cities are interconnected by railways, making people's lives more convenient and boosting the economy along the routes. In recent years, with the continuous expansion of the railway network, the standards and guidelines related to railway systems have also been updated, with RAMS (reliability, availability maintainability, safety) introduced to achieve sustainable development goals [1].



Figure 1.1: NS's Intercity train [2].

In this process, the train and track structures, along with their interactions, play a crucial role, as the railway operations rely on proper contact between wheels and rails. Wheel-rail contact on the one hand guides the train to travel along the track, and on the other hand, provides traction and braking forces to accelerate and stop as scheduled. When impact or sliding occurs at the wheel-rail contact due to e.g. geometrical/stiffness irregularities or poor adhesion behaviours, wheel-rail interface deterioration and structural degradation

can be induced, which may then pose a threat to the safety and punctuality of railway operations.

There are various forms of impact sources, including wheel flats, insulation rail joints, hanging sleepers, squats, and turnouts. Among them, the wheel flat is a common sliding-induced localized defect that can cause periodic wheel-rail impacts, consequent high-frequency vibrations and noise [3], long-section track damage, and instant rail breaks [4]. A severe wheel flat on a Chinese high-speed train and a large flat without notable martensitic transformation are shown in Figure 1.2 [5][6]. The impact of wheel flats on maintenance costs is substantial. In the last century, the North American railway industry annually invested considerable resources to replace approximately 124,800 wheelsets that failed to meet AAR (Association of American Railroads) rules [7]. The large-scale replacement of wheel sets also implies increased life-cycle emissions, which are not negligible [8]. Therefore, investigating the impact of wheel flats on wheel–rail interactions and developing effective monitoring methods and strategies for wheel flats are essential for ensuring safe, cost-efficient, and sustainable railway operations.

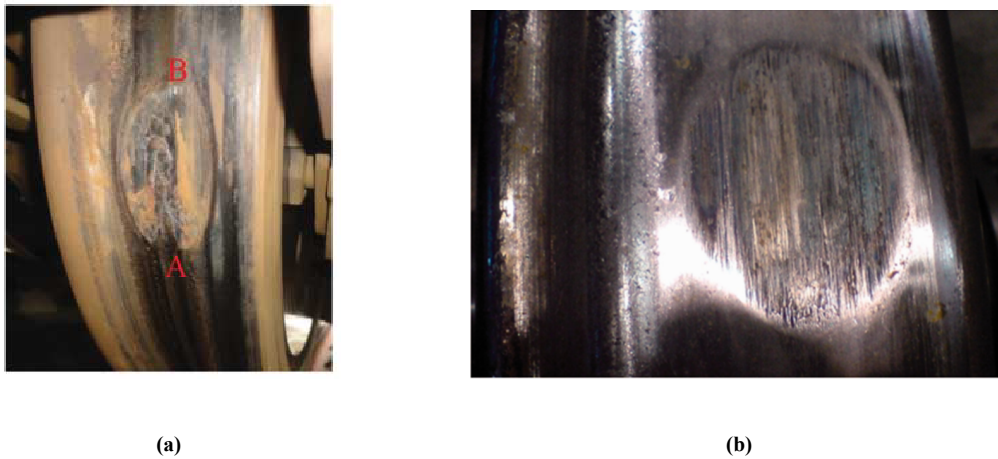


Figure 1.2: Wheel flats: (a) A severe wheel flat on a Chinese train [5]; (b) A large flat in winter conditions [6].

Currently, the monitoring of tread defects such as wheel flats is typically categorized into three main approaches: direct measurement, wayside methods, and train-borne methods. With the continuous advancement of the railway industry, an increasing number of trains are being equipped with various sensors, providing a solid foundation for the further development of train-borne monitoring techniques [9]. Axle box acceleration (ABA) systems, as a representative train-borne method, have been widely applied in the monitoring of track structures [10][11][12][13]. Similarly, ABA systems can also be used to monitor vehicles, particularly for detecting defects such as wheel flats, where they show considerable potential. Compared to traditional wayside systems, sensors are positioned closer to the wheel, which helps reduce the influence of external factors. Moreover, when combined with direct measurements, ABA systems provide the capability for early detection of wheel flats, which is valuable for the development of effective maintenance strategies.

1.2. Research Problem

There has been extensive research on wheel flats, with detailed discussions provided in Chapter 2 (Literature Review). These studies can generally be categorized into three main groups. The first group focuses on the formation mechanisms and contact behaviours of wheel flats. To this end, researchers have developed analytical and numerical models, or conducted extensive parametric studies through experiments [3][5][14]. The second group pertains to the ABA monitoring systems. In this category, the measured signals are obtained through field tests or simulations, and specific feature extraction methods are employed to diagnose wheel flats [15]. The third group focuses on wheel assessment rules established in different countries and regions. In these regulations, either the geometric parameters of the flat or the flat-induced impact force is used as the basis for maintenance decisions [9][16].

It is worth noting that the development of ABA-based wheel assessment rules is still in its early stages, primarily due to the unclear relationship between wheel flat severity, rolling speed, and monitoring data, particularly ABA signals and flat-induced impact forces. Addressing this issue requires the establishment of reliable models, the acquisition of precise test data, and the identification of the relationships between key parameters and system responses, all of which remain challenging tasks. To reliably model the impact characteristics caused by wheel flats on railway structures and then effectively monitor wheel flats, this study combines laboratory experiments and numerical simulations to conduct a parametric study examining the axle box acceleration and contact force responses induced by wheel flats with varying geometries and rolling speeds, providing insights for the development of wheel condition monitoring strategies.

1.3. Research Objectives

This study has three research objectives. The first is to develop an explicit finite element (FE) model and incorporate wheel flats of various geometric dimensions into the model based on the lab scan data. The second objective is to validate that the developed FE model can simulate the wheel–rail impact contact induced by wheel flats, using experimental results. The third objective is to conduct a parametric study to investigate the effects of rolling speed, flat length, and development stage on the impact response, including ABA features and impact forces, and to identify the characteristic frequency ranges relevant to flat-induced impact, thereby providing insights into wheel condition monitoring.

1.4. Research Scope

There are different models and test rigs designed for vehicle-track interactions worldwide, as well as various shapes and sizes of wheel flats. This study particularly focuses on the V-Track test rig, an in-house test rig designed by Delft University of Technology. It is shown

in Figure 1.3. In the experiments conducted in V-Track, the wheel flat shown in this figure was generated and tested at different speeds. The parameters of V-Track and the wheel flat were then used to establish the FE model and conduct numerical simulations. Furthermore, the measured signals collected by various forms of sensors can be used for the validation.

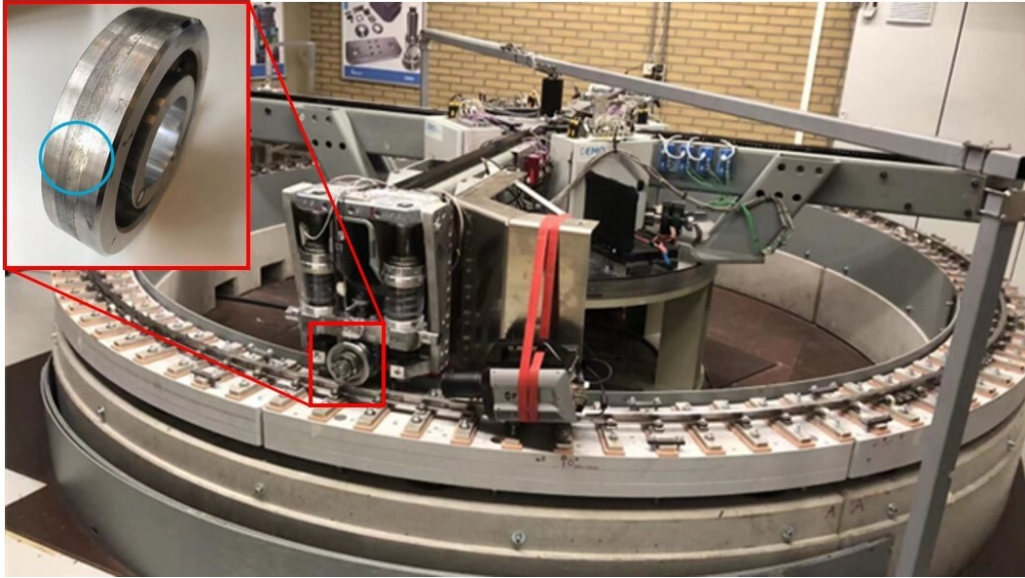


Figure 1.3: V-Track test rig and the wheel with a flat.

1.5. Research Questions

Main question:

How to effectively monitor wheel flats using ABA-based methods?

Sub questions:

- How do different rolling speeds, flat lengths, and development stages affect flat-induced impact responses, specifically the ABA features and wheel-rail contact force?
- Can wheel flats be effectively monitored solely using the ABA features, or is it necessary to incorporate additional monitoring indicators?

1.6. Research Structure

The thesis consists of 9 chapters and appendices. The structure is shown in Figure 1.4.

Chapter 1. Introduction

This chapter presents the research context, identifies the research problems, outlines the research objectives and scope, formulates the research questions, and describes the research

methodology.

Chapter 2. Literature Review

This chapter provides an overview of research related to the characteristics, modelling, and condition monitoring of wheel flats, as well as regulations and standards developed for wheel defect assessment.

Chapter 3. Method

This chapter summarises the methods used in this study, including model establishment, finite element analysis, and signal processing techniques.

Chapter 4. Model Validation

This chapter presents the model validation process, carried out by comparing the measured results with the simulation outputs.

Chapter 5. Effects of Speed

This chapter investigates the effects of wheel rolling speed on ABA and impact force, and identifies the signature tones of wheel flats.

Chapter 6. Effects of Flat Length

This chapter investigates the effects of flat length on ABA and impact force, and uses the SAWP to extract the features of the chosen scale range.

Chapter 7. Effects of Development Stage

This chapter investigates the effects of flat development stage on ABA and impact force and discusses the response changes due to the wear of flat edges.

Chapter 8. Conclusions and Recommendations

This chapter provides the conclusions of this study, and offers recommendations based on the current findings, especially the relationship between the wheel flat properties and monitoring indicators.

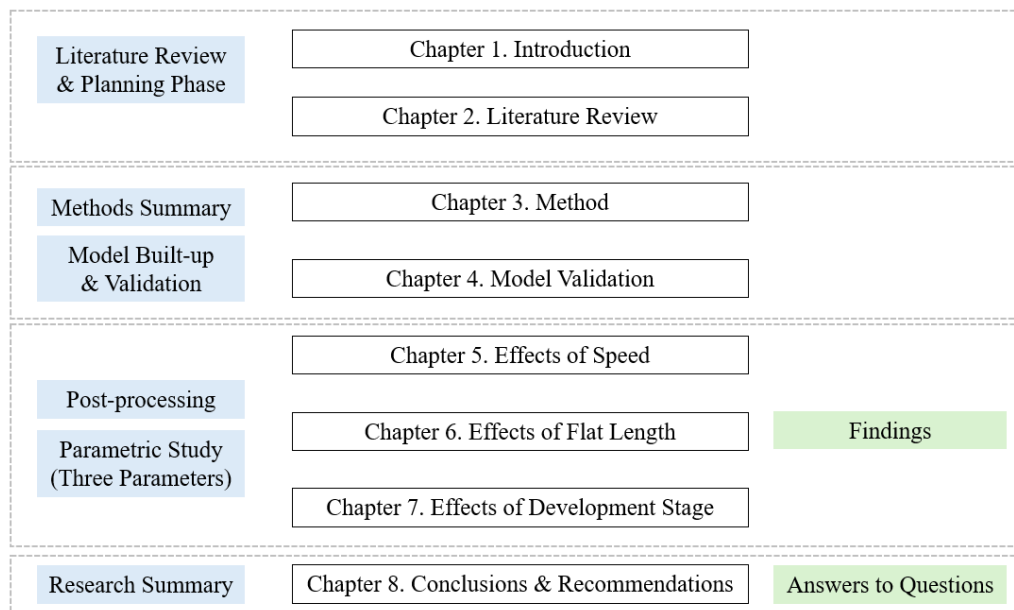


Figure 1.4: Research structure.

1.7. Research Methodology

The research methodology of this study is shown in Figure 1.5.

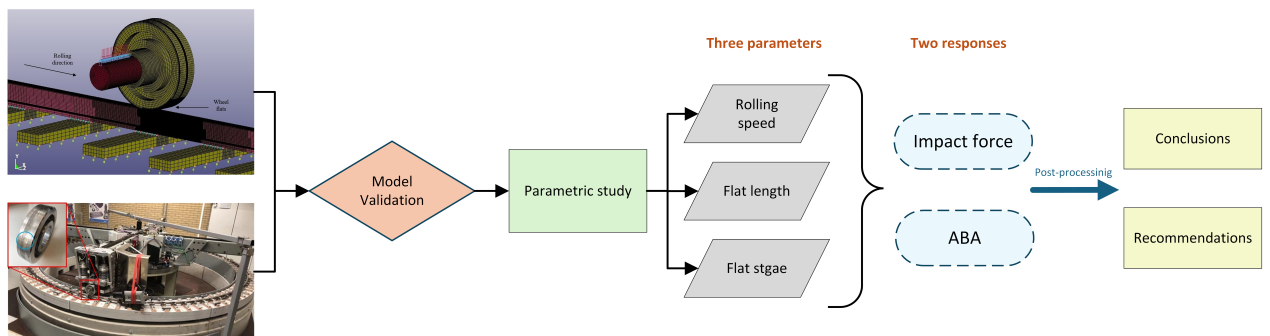


Figure 1.5: Research methodology.

2

Literature Review

This chapter provides a review of the relevant literature, including studies on wheel flats, ABA-based railway condition monitoring, and regulations developed for wheel defect assessment. These studies offer a solid conceptual and theoretical foundation for the present work.

2.1. Flat-induced Wheel-rail impact contact

Numerous studies have been conducted to investigate the effects of wheel flats on railway systems, with particular attention to the impact contact induced by flats. As part of these efforts, many researchers have performed experiments to gain deeper insights into this phenomenon. Newton et al. [17] investigated the dynamic effects of wheel flats on railway tracks through a controlled field experiment by British Rail. The experimental data validated the model with discrete support and Timoshenko beam, and showed that higher speeds led to full loss of wheel-rail contact and strong impact loads shown in Figure 2.1.

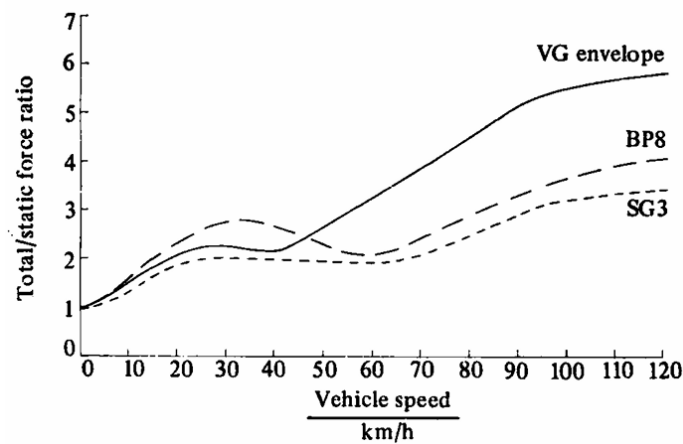


Figure 2.1: The measured peak responses versus speed [17].

Jerg us et al. [14] conducted extensive field experiments to investigate the structural damage and dynamic responses caused by wheel flats intentionally introduced on freight wheels. The test train is shown in Figure 2.2. Results indicate that impact forces increase with flat size and speed. The risk of wheel spalling and the significance of early detection are highlighted.

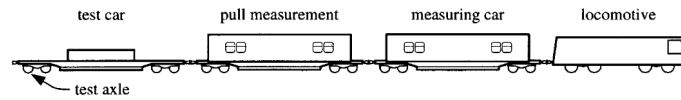


Figure 2.2: Test train [14].

Due to the complexity of the field conditions, it was, however, quite challenging to distinguish and assess the impacts of wheel flat geometries/severities, and speeds on the measured structural responses. This can be better tackled with the modelling of wheel-flat-induced impacts, analytically or numerically. For instance, Wu et al. [3] developed a numerical model to simulate wheel-rail impact caused by flats. The rolling process of a wheel with an idealized flat is illustrated in the Figure 2.3. A relative displacement, which can also be interpreted as the trajectory of the wheel centre, was introduced to represent the flat-induced excitation. The results show that a rounded flat can effectively reduce the peak impact force.

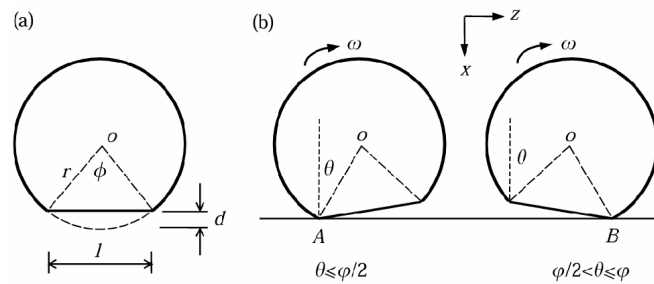


Figure 2.3: Rolling wheel with a newly formed flat [3].

Steenbergen [18] proposed an analytical model to investigate the influences of the wheel flat geometry and wheel velocity on wheel-rail impact forces. He proposed a critical wheel rolling speed, above which the wheel and rail may lose contact in the transcritical speed regime. As shown in Figure 2.4, in the subcritical speed range, the impact force increases more rapidly with rolling speed.

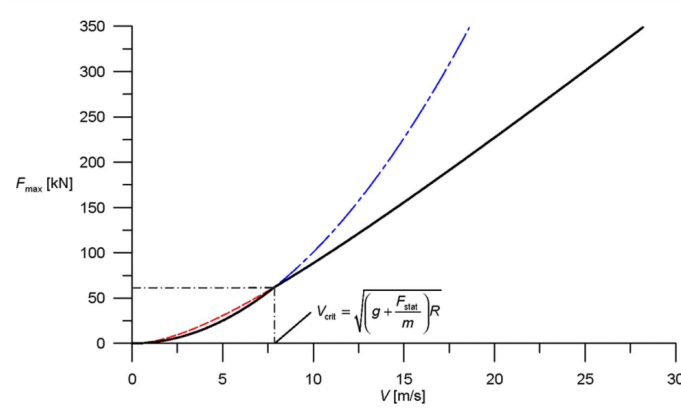


Figure 2.4: Impact force vs. train speed [18].

To further study the flat geometrical parameters, Ren et al. [5] developed a vehicle-track coupling model to simulate 3D wheel flats shown in Figure 2.5, and analysed the influences of the flat width and width/length ratio on wheel-rail impact forces. The vehicle is modelled as a rigid body, while the track is primarily represented using Euler–Bernoulli beams. For flats with different width-to-length ratios, the corresponding safe speed ranges were proposed.

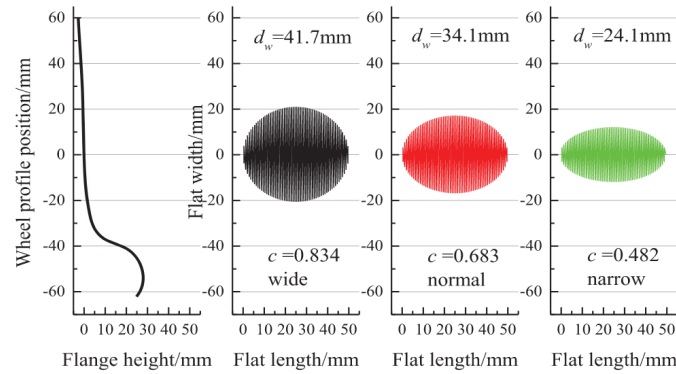


Figure 2.5: Discretized 3D wheel flats [5].

In addition to the contact force, the wheel/rail acceleration is also a significant impact response. When an impact occurs, both the vehicle and the track experience sudden changes in acceleration in the vertical and longitudinal directions. Capturing these changes using accelerometers enables effective detection of abnormalities. Section 2.2 provides a detailed overview of research in this area. Uzzal et al. [19] established a three-dimensional vehicle–track interaction model incorporating two-dimensional haversine-shaped flats. In this model, the track is represented by Timoshenko beams, and the vehicle is simplified as a rigid body with 17 degrees of freedom. As shown in Figure 2.6, the resulting flat-induced wheel accelerations are clearly identifiable.

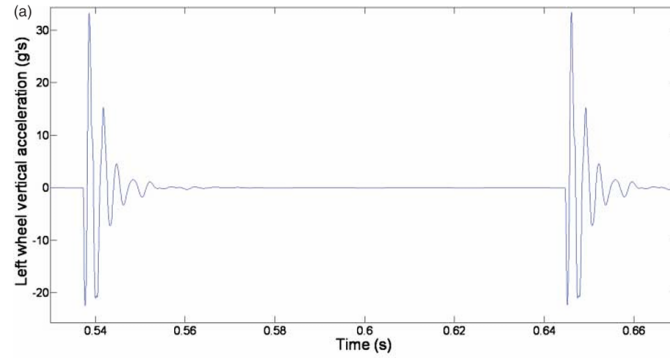


Figure 2.6: Wheel vertical accelerations [19].

Based on the reviewed studies, it can be observed that various forms of contact models have been developed to analyse flat-induced wheel–rail interactions, including both 2D and 3D contact models, as well as Hertzian and non-Hertzian contact models. Pieringer et al. [20] compared the impact force responses of different models and found that the 2D non-Hertzian model underestimated, while the 3D non-Hertzian model overestimated the peak impact force. The longitudinal geometry of the wheel flat may play a critical role in this process, as even small variations can lead to significant differences in the response.

Apart from contact modelling, the modelling of both the vehicle and the track also plays a critical role and can significantly influence the simulation results. In general, rails are commonly modelled as beams, such as Timoshenko beams or Euler–Bernoulli beams. In recent years, more studies have adopted continuum models, such as 3D FE models, to investigate wheel–rail impact contact problems [21]. Chen et al. [22] compared continuum and beam models in addressing surface defect–induced impacts, and their results indicated that the continuum model offers higher accuracy. In this study, a continuum model is employed to analyse flat-induced impacts.

2.2. ABA Monitoring Systems

In recent years, to closely monitor wheel flats and thus mitigate their adverse impacts on railway structures, increasing research has been reported aiming to identify the measurement signal characteristics induced by wheel flats based on the measurement of ABA. ABA, as a cost-effective train-borne measurement system, has been used since the last century on Dutch railways to detect faulty welds [23]. The layout of the ABA system is shown in Figure 2.7 [13]. Accelerations in three directions can be collected simultaneously. Combined with GPS, accurate positional information can be obtained to locate target defects.

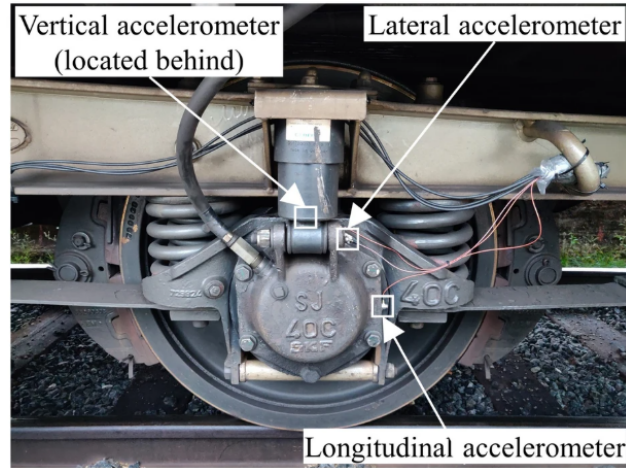


Figure 2.7: The layout of the ABA system [13].

The ABA-based approach has been proven effective for railway defect detection, such as at squats [24], degraded rail joints [25], transition zones [13][26] corrugations [27], and welds [28]. To enable the use of ABA for detecting short-pitch corrugations, Li et al. [12] developed an automated algorithm to assess the possibility of corrugation occurrence. The method was validated on the Dutch railway line between Assen and Groningen, as shown in Figure 2.8.

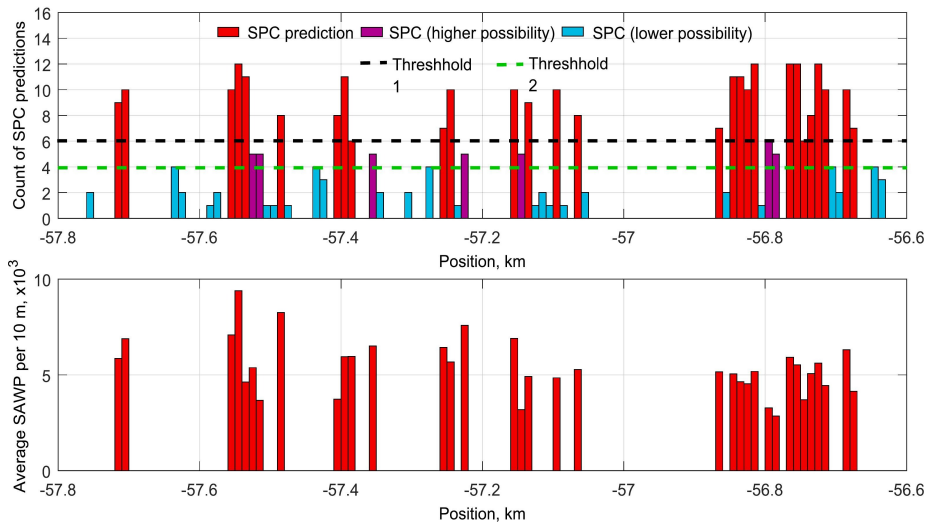


Figure 2.8: Prediction of short pitch corrugation (SPC) [12].

Returning to the monitoring of wheel flats using ABA, a lot of methods have emerged in recent years. In order to extract impact features related to flat-induced excitations from ABA signals, Liang et al. [29] investigated three commonly used time-frequency techniques: Short-Time Fourier Transform, Wavelet transform, and Wigner–Ville transform. The results indicate that Wavelet transform can provide the best time-frequency localization and effectively separate the defect signals, as shown in Figure 2.9.

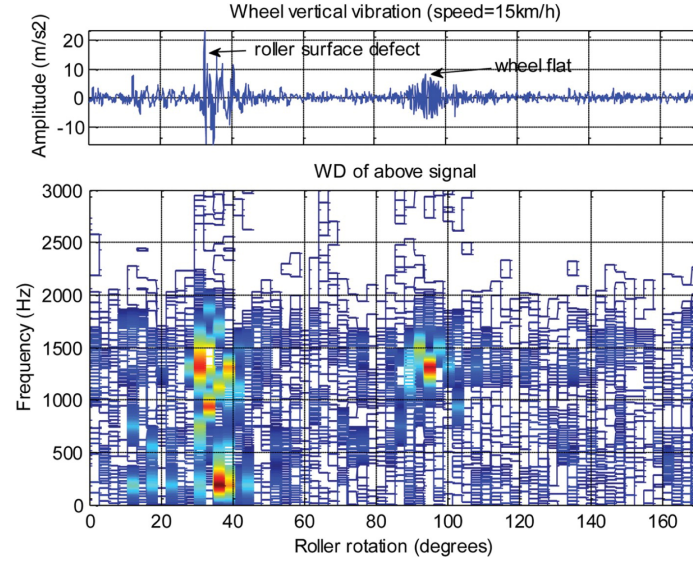


Figure 2.9: Wavelet transform of wheel acceleration [29].

Bosso et al. [30] designed a time-domain detection algorithm specifically targeting wheel flats through the use of maximum and root mean square (RMS) axle box accelerations, which can indicate the flat severity. The developed wheel flat severity index (WFI) is shown in Equation (2.1). A higher WFI implies a larger transient deviation from the average vibration level. The algorithm was validated through both multi-body dynamic simulations and field tests, both of which took track irregularities into account. The freight train used for tests is shown in Figure 2.10. Field tests indicate that establishing a clear relationship between flat length and the defined ABA indicator remains challenging.

$$\text{WFI} = \ddot{A}_{m,\max} - \ddot{A}_{m,\text{rms}} \geq 0 \quad (2.1)$$



Figure 2.10: The unloaded freight train with wheel flats [30].

To further establish the connection between wheel flat parameters and monitoring data, Ye et al. [15] proposed a data-driven KSM-PSO model based on the simulated ABA data to discover the relationship between speeds, flat length, and maximum ABA amplitude, as shown in Figure 2.11. In the adopted multi-body system model, the defect was simply

represented as two-dimensional haversine flats. Finally, the data-driven model was validated on the German railway network. The error analysis revealed that rigid components, environmental factors, and other non-linear effects can all contribute to measurement inaccuracies.

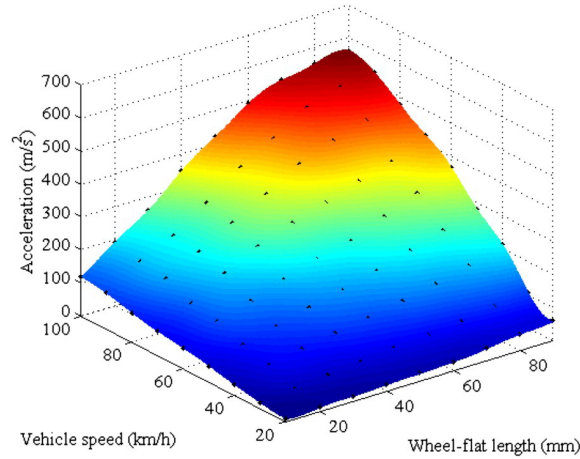


Figure 2.11: Wheel-flat Kriging surrogate model [15].

Considering the periodic characteristics of flat-induced structural responses, Zhou et al. [31] innovatively transformed the ABA signal into the angular domain and applied a synchronous averaging method to reduce the influence of other excitations. This approach was validated through experiments and multi-body dynamic simulations. The results showed that the angular domain synchronous averaging (ADSA) method is insensitive to small-sized wheel flats.

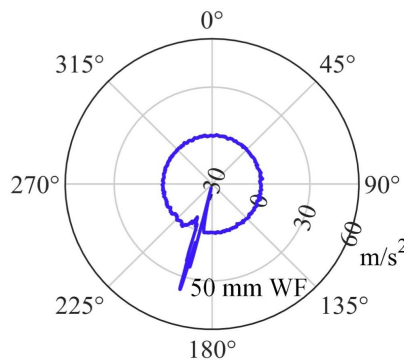


Figure 2.12: ADSA results of the axle box [31].

In summary, the use of ABA systems for monitoring wheel conditions, particularly tread defects such as wheel flats, still presents considerable research potential. Further studies are needed in experimental approaches, numerical simulations, and data post-processing techniques.

2.3. Regulations for Wheel Defect Assessment

Wheel flats are among the most common types of wheel defects, and many countries have established specific regulations for their assessment. The geometry of a wheel flat, particularly its length and depth, is relatively easy to quantify and is commonly used as a basis for determining the severity of the defect, as well as for deciding whether a wheelset needs to be removed from service. In the United States, AAR specifies that the length of a single flat must not exceed 50.8 mm. When two adjacent flats are present, the length of each must not exceed 38.1 mm [32]. Compared to the AAR regulations, the safety rules established by the Canadian government are more lenient. The allowable length for a single flat is up to 63.5 mm, while for two adjacent flats, the length of each must not exceed 50.8 mm [33]. In Britain, the Rail Safety and Standards Board (RSSB) has established specific actions to be taken based on the type of vehicle and the length of the wheel flat. For example, in the case of a passenger train operating at speeds exceeding 201 km/h, a wheel flat measuring between 40 and 60 mm does not require immediate removal but must be addressed within 24 hours [34]. Sweden and Italy have adopted the same approach, requiring the removal of wheelsets when the wheel flat length exceeds 40 mm [16][35].

Although using wheel flat length as an assessment indicator is intuitive and reliable, measuring the wheel profile with specialized instruments in practical operations is not a straightforward task [9]. As a result, researchers have explored the use of wheel–rail impact forces to monitor abnormal wheel profiles. The Wheel Impact Load Detector (WILD), a widely adopted wayside monitoring system, has been extensively used for this purpose. Alemi et al. [36] developed a WILD system consisting of multiple sensors mounted on the rail web to identify wheel defects. In fact, in various countries and regions, the impact force measured by WILDs can directly used as a trigger for defect alarms. For example, according to UIC regulations, when the axle load is 25 tonnes, wheel–rail impact forces exceeding 350 kN are not permitted [37]. It is important to note that several factors, such as the location of the WILD installation, the position at which the impact occurs, and the axle load, can significantly influence the measured impact force. A summary of wheel alarm regulations based on WILD systems adopted in different countries is provided in [9], as shown in Table 2.1.

Table 2.1: WILD-based wheel alarm regulations in different countries [9].

	Axle load [tonnes]	Alarm limit [kN]	Alert limit [kN]
Australia	30	400	—
China	30	$\alpha \geq 23^a$	$\alpha \in [21, 22]$
Finland	22.5 or 25	450	350
Sweden	30	350 ^b	280
Switzerland	22.5	400	300
UK	25	350 ^c	200
UIC	25	350	—

As mentioned in the previous section, train-borne measurements, such as ABA, have been increasingly applied in the field of railway monitoring, making it possible to detect wheel flats and identify key parameters using ABA data. However, this remains a challenging task, and no country or region has yet established official standards or regulations for such an approach. Therefore, the investigation of the relationships between the studied parameters and system responses in this study may offer valuable insights for the development of this field.

3

Method

This chapter consists of three sections. The first section focuses on the development of a 3D finite element model based on the V-Track test rig, in which the flat observed on the test wheel was incorporated into the model and parametrised to generate five cases for this study, representing various degrees of wear severity. The second section outlines the simulation process, introducing the implicit–explicit sequential solving strategy and discussing its effectiveness in handling transient wheel–rail contact problems. The third section presents the signal processing techniques employed in this study, with particular emphasis on time–frequency analysis methods.

3.1. 3D FE Model Establishment

3.1.1. V-Track Test Rig

In order to obtain the test data, especially the ABA data, the experimental study was conducted in V-Track using a wheel with a newly formed flat. V-Track is an in-house down-scale test rig. It was designed by Delft University of Technology to simulate continuous wheel-rail interactions and defect-induced high-frequency dynamic responses [38]. The CAD view of this test rig is shown in Figure 3.1. By employing an appropriate scaling strategy and a custom-made circular track, the V-Track is capable of effectively simulating long-term rolling contact. The dynamic characteristics of V-Track were further validated through hammer tests [38]. Furthermore, an ABA system and a dynamometer composed of force sensors were developed for V-Track to enhance its flexibility and controllability [39].

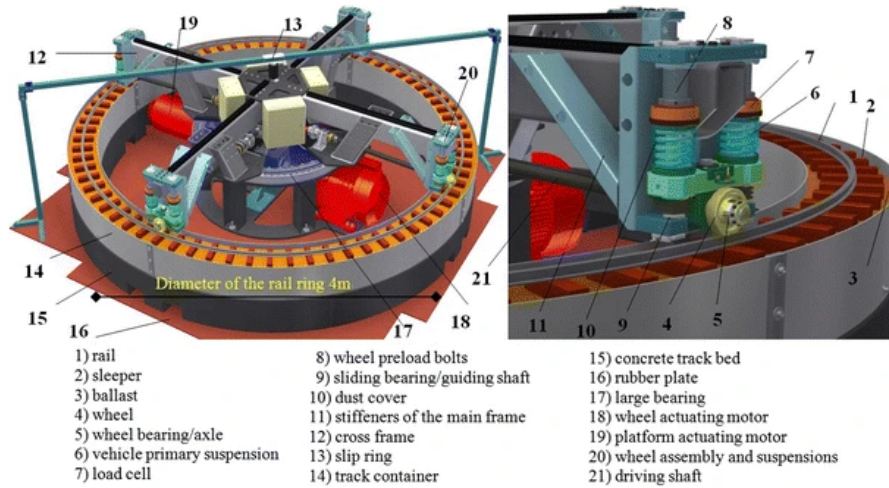


Figure 3.1: The CAD view of V-Track [38].

Through experiments, Zhang et al. [40] demonstrated that V-Track can be used to study short-pitch corrugation (SPC), a type of rail surface irregularity, and identified its formation mechanism. In a follow-up study, more experiments were conducted in V-Track to investigate new evidences for SPC formation [41]. An example of SPC observed in V-Track is shown in Figure 3.2.

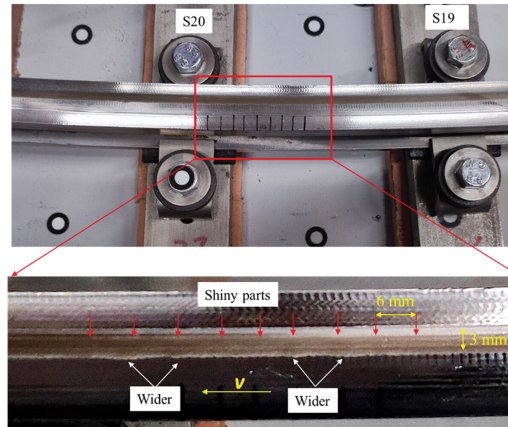


Figure 3.2: SPC on V-Track [41].

In addition to rail surface irregularities, V-Track can also be used to study wheel surface irregularities. He et al. [42] established a 3D FE thermomechanical model based on V-Track to study the wheel polygonal wear, a type of out-of-round (OOR) defect, and explored its initiation and development mechanisms under high-temperature conditions. The FE model is shown in Figure 3.3. To further validate this model, Zhang et al. [43] conducted a comprehensive validation by comparing data from hammer tests and rolling contact experiments with simulation results, demonstrating that the model is can capture high-frequency wheel–rail interactions. The simulated vertical track eigenmodes are shown in Table 3.1, and the identified wheel eigenmodes are shown in Figure 3.4. With a downscale factor of

1/5, the dynamic characteristics of the V-Track FE model correspond well to those of the actual train-track system.

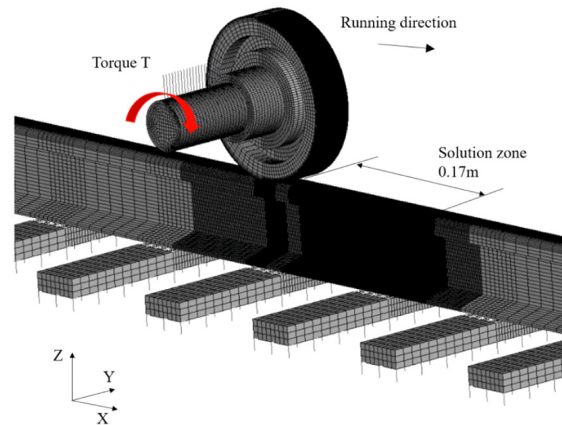


Figure 3.3: The 3D FE model of V-Track [42].

Table 3.1: Eigenmodes of the track structure.

Notations	Track eigenmodes
T_{1z}	Full track vertical resonance mode at 437 Hz
T_{2z}	Rail vertical bending mode at 583 Hz
T_{3z}	Sleeper 1st vertical bending mode at 1148 Hz
T_{4z}	Rail vertical resonance mode at 2479 Hz
T_{5z}	Rail vertical bending mode at 3128 Hz
T_{6z}	Vertical pinned-pinned resonance mode at 6280 Hz

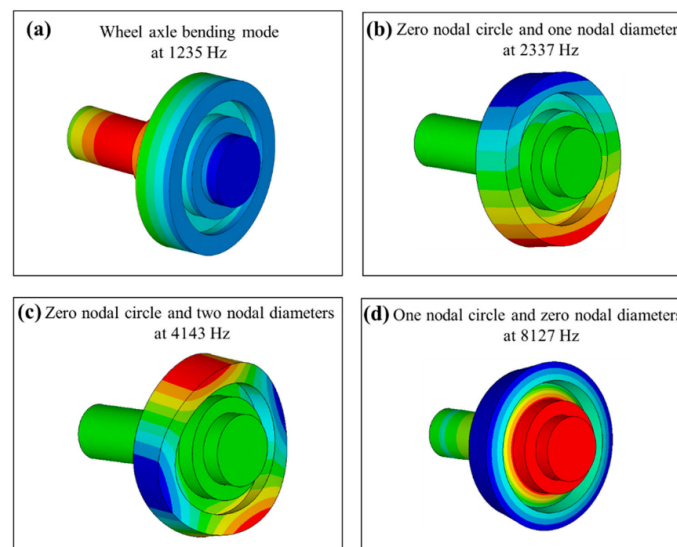


Figure 3.4: Four identified wheel eigenmodes [43].

3.1.2. Flat Modelling

After the experimental study, the wheel used in the test was first scanned to determine the basic parameters of the flat, followed by the construction of the FE model. The test rig, test wheel, and the corresponding flat are shown in the Figure 3.5.

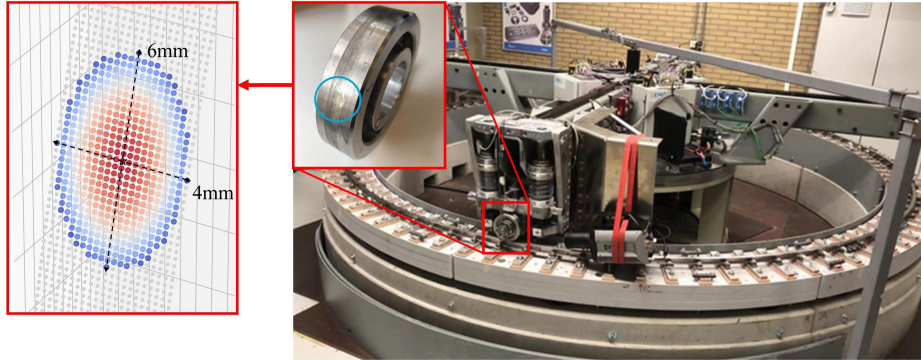


Figure 3.5: V-Track test rig with a wheel flat.

It can be observed that, in order to incorporate a real wheel flat into a FE model, especially a 3D FE model for a parametric study, parametrising the actual wheel flat is an effective approach. The first step of the parametrisation involves discretising the wheel flat along the tread direction, resulting in multiple cross-sections. Within the flat region, these cross-sections have different arc profiles. The detailed process is illustrated in Figure 3.6.

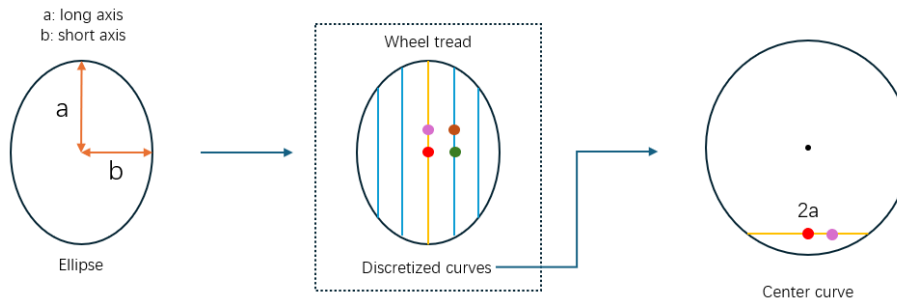


Figure 3.6: Discretisation of a wheel flat.

The example presented above is a fresh flat. In practice, as the edges of the flat undergo continuous wear, a fresh flat gradually evolves into a rounded flat. The shapes of both types of flats in 2D cross-section are shown in Figure 3.7, which is a schematic illustration. AOB represents a fresh flat, while COD corresponds to a rounded flat. The primary difference between the two lies in the change in curvature: in AOB, there is an abrupt change in curvature at both ends of the flat, whereas in COD, the transition is smooth. As shown in the figure, d denotes the wheel profile depth, which refers to the deviation between the original wheel surface and the flatted wheel surface.

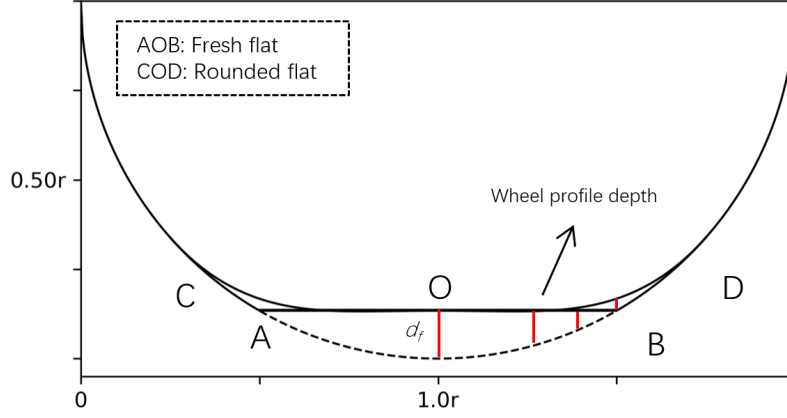


Figure 3.7: The scheme of 2D wheel flats.

Therefore, there are two cases for calculating the wheel profile depth. The first case is the fresh flat. Here, d_f refers to the maximum depth, which typically corresponds to the profile depth at the centre of the flat area. The vertical wheel profile depth of the fresh flat is given by:

$$p_{ff}(x) = d_f + \sqrt{r^2 - x^2} - r, \quad -\frac{l_0}{2} \leq x \leq \frac{l_0}{2} \quad (3.1)$$

where p_{ff} is the profile depth of a fresh flat, d_f is maximum depth, r is the wheel radius, x represents the horizontal distance from the flat centre, l_0 is the length of the fresh flat.

For the rounded flat, [17] proposed an approximation method using a haversine function. The vertical profile depth of the rounded flat is given by:

$$p_{rf}(x) = \frac{d_f}{2} \left(1 + \cos \left(2\pi \frac{x}{l} \right) \right), \quad -\frac{l}{2} \leq x \leq \frac{l}{2}. \quad (3.2)$$

where p_{rf} is the profile depth of a rounded flat, d_f is maximum depth, r is the wheel radius, x represents the horizontal distance from the flat centre, l is the length of the rounded flat.

Based on the above equations, the flat geometry for a single cross-section can be determined. In this study, five cases are considered, and the wheel profile depths at the central cross-section for each case are shown in Figure 3.8. The points here represent the nodes in the 3D FE model, with the coordinates updated due to the flat.

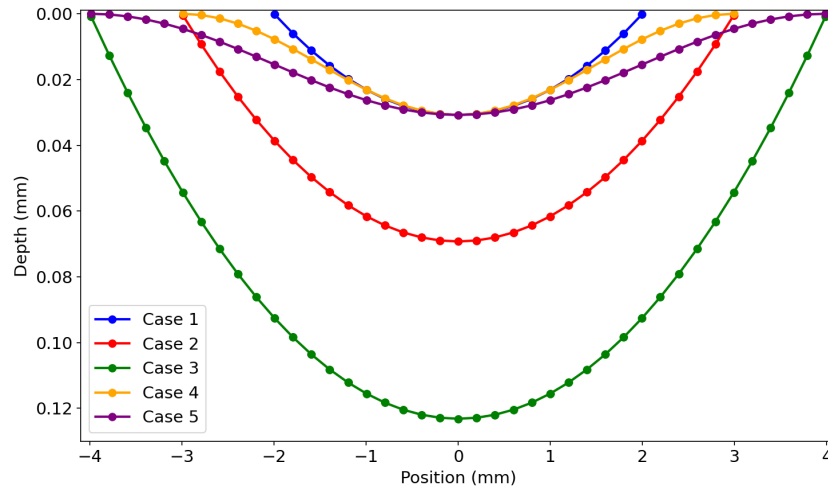


Figure 3.8: The wheel profile depths taken from the central cross-section.

However, at this stage, the wheel flat remains two-dimensional. To extend it into three dimensions, the flat must be projected along the width direction. In the adopted 3D FE model, the wheel tread and rail surface involved in the contact process are finely meshed, with an element length of 0.2 mm. Therefore, a new flat profile can be discretised every 0.2 mm. In these cross-sections, both the flat length and the profile depth gradually decrease toward the edges, eventually tapering to zero. In this way, an elliptical 3D wheel flat is constructed.

In this study, 5 cases were analysed. The parameters are listed in Table 3.2. The geometry of Case 2 corresponds to the measured geometry of a newly-formed wheel flat (i.e. fresh flat) in V-Track. Case 1 and Case 3 represent lighter and severer flat scenarios with decreasing and increasing length and depth, respectively. Considering that wear typically occurs at the edge of the flat area, while the central area remains unchanged [3], Case 4 has the same depth as Case 1, but the edge of the flat is rounded with a haversine curve to represent a worn flat. Case 5 also shares the same depth as Case 1, but its flat is even longer than that of Case 4. Therefore, Case 1, Case 4, and Case 5 correspond to the flat geometries at the early, mature, and most developed stages of wheel flat evolution, respectively. All cases share the same width.

Table 3.2: Wheel flat geometries of the simulation cases.

	Case 1	Case 2	Case 3	Case 4	Case 5
Type	Fresh	Fresh	Fresh	Rounded	Rounded
Length (mm)	4	6	8	6	8
Width (mm)	4	4	4	4	4
Depth (mm)	0.03	0.07	0.12	0.03	0.03

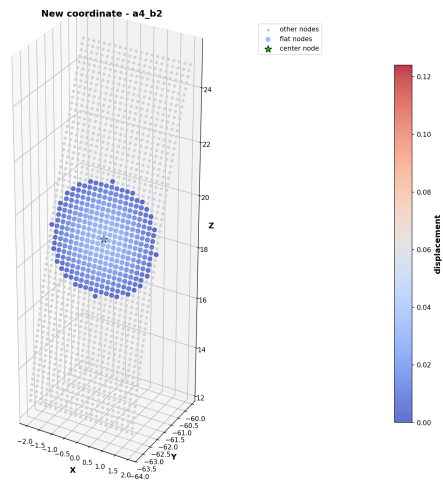


Figure 3.9: Nodal coordinate (Case 1).

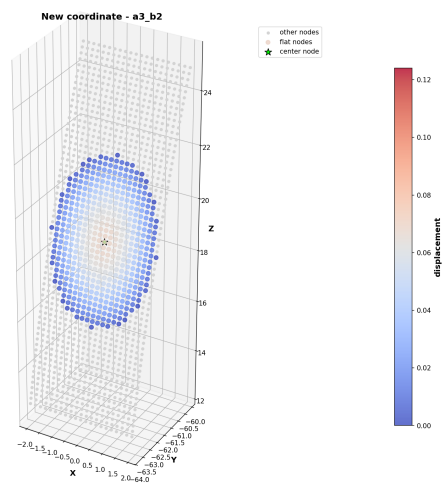


Figure 3.10: Nodal coordinate (Case 2).

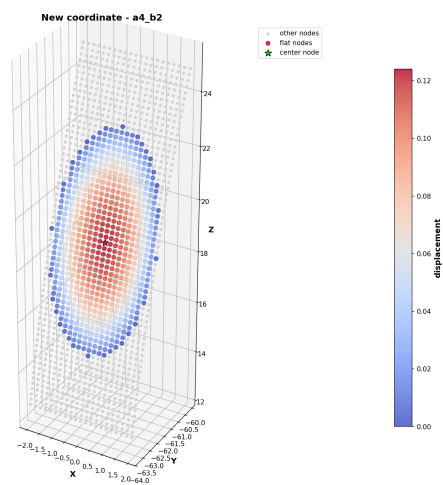


Figure 3.11: Nodal coordinate (Case 3).

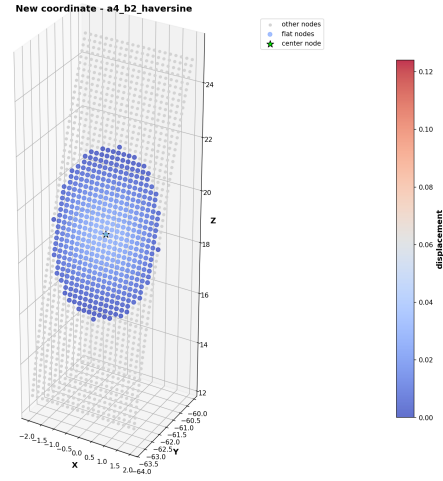


Figure 3.12: Nodal coordinate (Case 4).

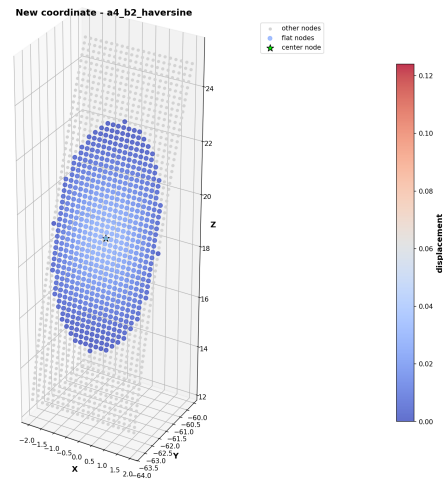


Figure 3.13: Nodal coordinate (Case 5).

Figure 3.9 to Figure 3.13 show the transformed coordinates of the 3D wheel flats to match the coordinate system of the FE model. The colour at each point represents the displacement magnitude, which is referred to as the profile depth, at the corresponding node. The 3D plot clearly illustrates that the displacement differences among nodes at different positions of the rounded flat are minimal, and the transition between the flat and non-flat areas is smooth. The final flat area and the complete 3D explicit FE model are shown in Figure 3.14. It can be observed that the fine mesh in the tread region can effectively reflect the flat shape, although it will take more time to finish the simulations.

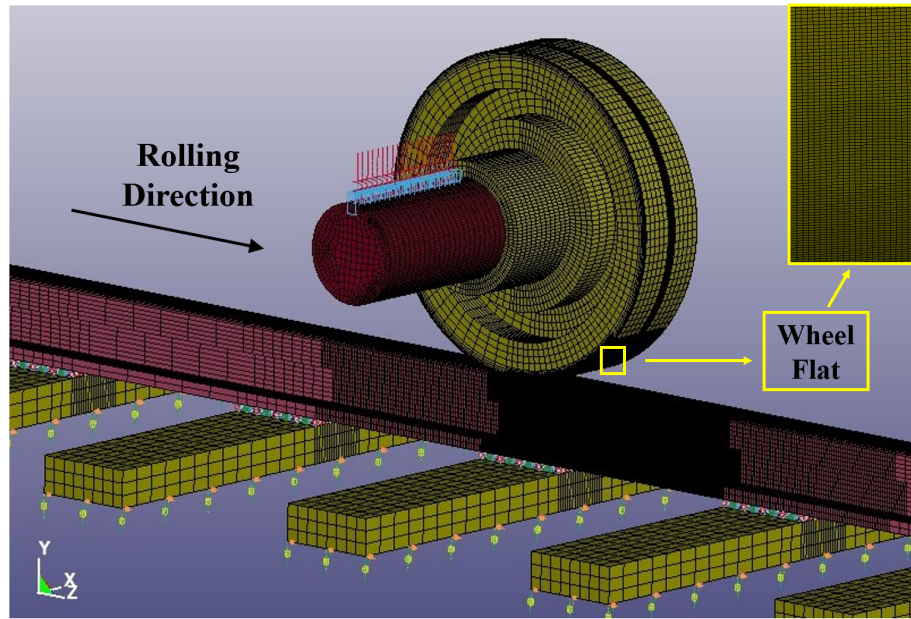


Figure 3.14: The developed 3D FE model for flat-induced wheel-rail interactions.

The 3D FE model consists of 646016 nodes, 566292 8-node solid elements, 8572 discrete elements, 20 mass elements, and 4 beam elements. The axle Z refers to the rolling direction. A mesh size of 0.2 mm is applied to the wheel tread and rail surface areas involved in the surface-to-surface contact process, to ensure the precision of contact solutions and flat modelling. To better simulate track dynamics using the 3D FE model, both the fastenings and the ballast are modelled as spring-damper systems in three directions. The vehicle load is simplified into three components: the self-weight of the wheel, the weight of the mass element representing the axle box, and the force resulting from the initial offset of the primary suspension. The key parameters are shown in Table 3.3.

Table 3.3: Key parameters of the 3D FE model.

Parameters	Values	Units
Density of wheel, rail, and sleepers	7800	(kg/m ³)
Young's modulus	210	(GPa)
Poisson's ratio	0.3	/
Offset of the primary suspension	0.0174	(m)
Stiffness of the primary suspension	10.5	(kN/m)
Damping of the primary suspension	5	(N·s/m)
Weight of one mass element	2	(kg)
Radius of wheel	65	(mm)
Principal radius of rail	60	(mm)
Coefficient of friction	0.45	/

3.2. Implicit-explicit Sequential Approach

In order to simulate the flat-induced wheel-rail interactions, an implicit-explicit sequential approach is employed. It can reduce computation time and save computational resources. This method was proven effective for solving transient wheel-rail contact problems [42][43][44][45][46].

In the implicit analysis, the wheel is constrained to move only in the vertical direction, and the initial nodal displacements are obtained through the static equilibrium for the dynamic relaxation. It can also be used to verify the accuracy of the model in terms of contact forces. After the system reaches equilibrium, the maximum normal contact pressure between the wheel and rail is shown in the figure to be 1.343GPa , which deviates by less than 5% from the solution predicted by the traditional elliptical Hertzian contact theory. [47]. The results are not exactly the same, as the 3D FE model has more structural components, and features more complex boundary conditions. The assumptions of frictionless contact and half-space geometry are not satisfied.

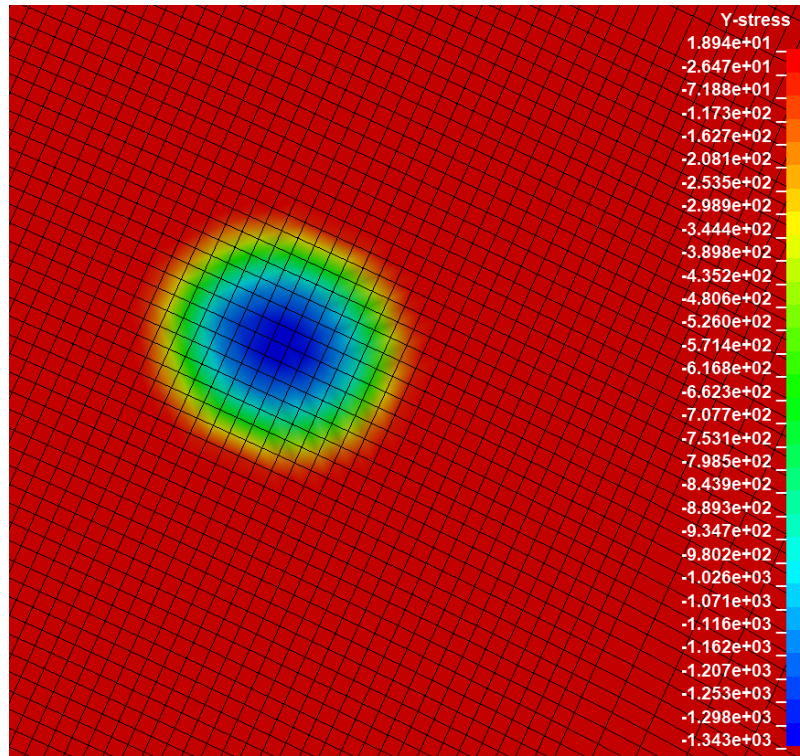


Figure 3.15: Contact stress contour in the implicit analysis.

In the subsequent explicit analysis, the longitudinal degree of freedom is released, and initial translational and rotational velocities are applied to the wheel to initiate rolling. Taking the simulation at 16 km/h as an example, the wheel is assigned an initial translational speed of 16 km/h (4444 mm/s) and an initial rotational speed of 68.38 rad/s. The same initial translational speed is also applied to the other vehicle components. Then the torque is applied to the wheel to generate traction conditions.

3.3. Signal Processing

3.3.1. CWT and Features

When a wheel flat is present, the acquired ABA signal becomes non-stationary. To better extract impact-related information from the ABA data, time–frequency analysis techniques are necessary. The first method used is the Continuous Wavelet Transform (CWT). The CWT provides good time and frequency resolutions, making it suitable for accurately identifying local fluctuations in the signal. Energy concentration caused by wheel–rail impacts can thus be effectively captured. It can be calculated as [48]:

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi^* \left(\frac{(n' - n) \delta_t}{s} \right) \quad (3.3)$$

where $x_{n'}$ is the discrete-time signal (such as measured or simulated data), δ_t is the sampling interval, s is the scale factor ($s > 0$), and $W_n(s)$ denotes the wavelet coefficient, ψ is a family of wavelets, $*$ refers to the complex conjugate.

In this study, the Morlet function is used as the mother wavelet. It is well suited for capturing the local time-frequency characteristics of the signal. The wavelet power spectrum (WPS) is the product of the wavelet coefficients given by:

$$WPS = |W_n(s)|^2 \quad (3.4)$$

Then, the global wavelet power spectrum (GWPS), which is time-averaged, can be extracted from the WPS to further investigate the dominant frequency characteristics. The GWPS is defined as [48]:

$$GWPS = \frac{1}{N} \sum_{n=0}^{N-1} |W_n(s)|^2 \quad (3.5)$$

The scale average wavelet power (SAWP), which is scale-averaged, can also be extracted from the WPS. The SAWP has been shown to be effective for monitoring squats and short-pitch corrugations, indicating its capability to examine fluctuations over scales [24][12]. The SAWP can be calculated as [48]:

$$SAWP = \frac{\delta_j \delta_t}{C_\delta} \sum_{j=j_1}^{j_2} \frac{|W_n(s_j)|^2}{s_j} \quad (3.6)$$

where δ_j is the scale step, δ_t is the sampling interval, C_δ is a constant related to the wavelet function.

3.3.2. SSWT and Features

Compared to the CWT, the Synchrosqueezed Wavelet transform (SSWT) applies a post-processing technique that redistributes the energy into narrower frequency bands, thereby facilitating the identification of dominant frequency components. The SSWT is defined as [49]:

$$T_s(\omega_\ell, b) = (\Delta\omega)^{-1} \sum_{\substack{a_k: \\ |\omega(a_k, b) - \omega_\ell| \leq \Delta\omega/2}} W_s(a_k, b) a_k^{-3/2} (\Delta a)_k. \quad (3.7)$$

where $\omega(a_k, b)$ is the instantaneous frequency obtained from the CWT. Based on the SSWT, the local wavelet power spectrum (LWPS) can be derived to exhibit the wavelet power averaged over a determined distance range. It can further extract frequency peaks that are not easily detectable by conventional methods. It is given by [50]:

$$LWPS = \frac{1}{n_{\Delta d}} \sum_{x_w=d_1}^{d_2} |T_s^2(f, x_w)| \quad (3.8)$$

where n is the number of points within the selected window.

4

Model Validation

As mentioned above, the original 3D FE V-Track model without considering the wheel flat has been thoroughly validated through simulations and experiments in previous studies [42][43]. To ensure that the newly developed FE model is capable of accurately capturing the impact responses induced by wheel flats, simulation results were compared with corresponding measurement data obtained from the V-Track experiments. This comparison serves to validate the model's ability to replicate the dynamic behaviour associated with flat-rail interactions under realistic operating conditions.

Due to laboratory safety rules, the maximum speed for the flat-induced wheel-rail rolling contact experiments conducted on V-Track was limited to 16 km/h. A schematic diagram of the circular track, which has a diameter of 4 metres, is shown in Figure 4.1. The track consists of five sections, five rail joints, and evenly distributed sleepers and fastenings [42]. The insulation rail joints (IRJs), as a form of short-wavelength defect, also contribute to wheel-rail impact and interact with the flat-induced impact.

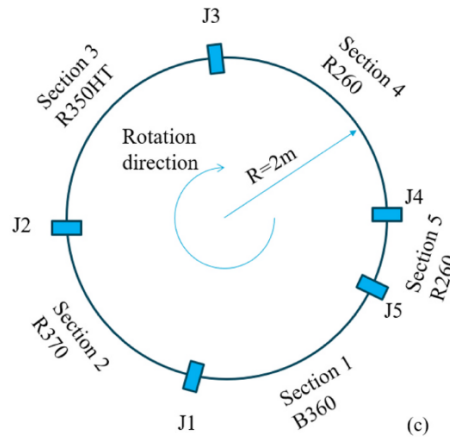


Figure 4.1: The schematic diagram of the circular track [42].

Based on the impact intervals, target signal segments suitable for further analysis can be

identified. Taking the experimental data at 4 km/h as an example, the measured vertical ABA signal is shown in Figure 4.2. Based on the wheel rolling speed and wheel radius, the interval between successive impacts is calculated to be approximately 0.368 seconds. As shown in the figure, the periodic acceleration peaks are clearly identifiable, and by comparing the time intervals, the flat-induced impacts can be isolated. Therefore, the wheel flat monitoring can be intuitively achieved by identifying periodic short-duration high-frequency responses. However, these results were obtained under controlled laboratory conditions. In real-world scenarios, time-domain signals are influenced by various additional factors, such as the presence of rail defects and variations in track structural properties. This highlights the need to further investigate the relationship between defect parameters and features in the monitoring data, which requires analysis in both the time and time–frequency domains.

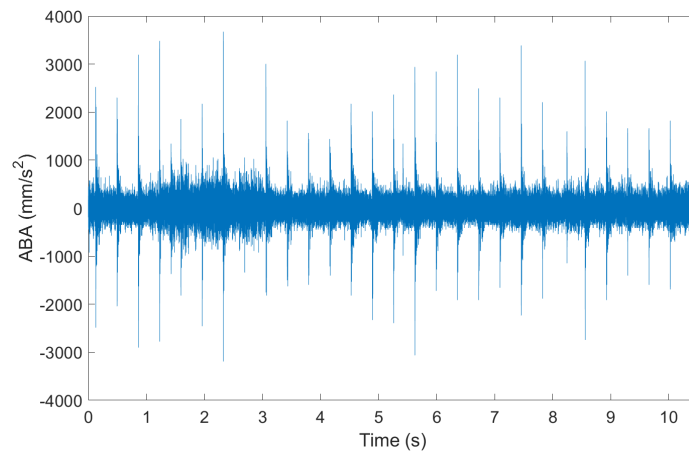


Figure 4.2: The measured vertical ABA at 4 km/h.

When the speed increases from 4 km/h to 8 km/h, the measured vertical ABA signal shows that the impact interval is approximately 0.185 seconds. As the speed doubles, the interval between impacts is halved. Under laboratory conditions, the periodic nature of wheel flats is clearly demonstrated.

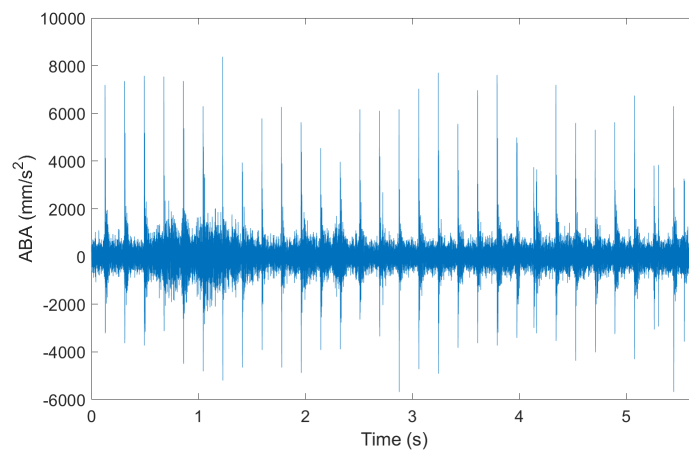


Figure 4.3: The measured vertical ABA at 8 km/h.

In order to validate the developed 3D FE model, the measured ABA at a speed of 16 km/h is used. As mentioned in Chapter 3, there are five different simulation cases with different flat geometries. Case 2, which has parameters most consistent with the test wheel, is used for comparisons with the experimental data. A single impact segment is selected as the target for analysis. All the ABA signals were processed using a fourth-order Butterworth low-pass filter with a cut-off frequency of 10000 Hz before the time-frequency analyses.

After filtering, the simulated and measured vertical ABA signals were processed using the CWT, and the resulting WPSs are compared in Figure 4.4. Both sets of signals indicate the flat-induced impact process, which takes place within the range of approximately 20 to 40 mm. The CWT provides the detailed time-domain and frequency-domain information. It can be observed that, compared to the simulated ABA signal, which exhibits a concentrated vibration energy around 1 kHz, the measured ABA displays a broader energy distribution, spanning from approximately 400 Hz to 1 kHz. This discrepancy may be attributed to additional sources of excitations present in the experimental setup. A more detailed explanation of this difference is provided through the subsequent SSWT analysis.

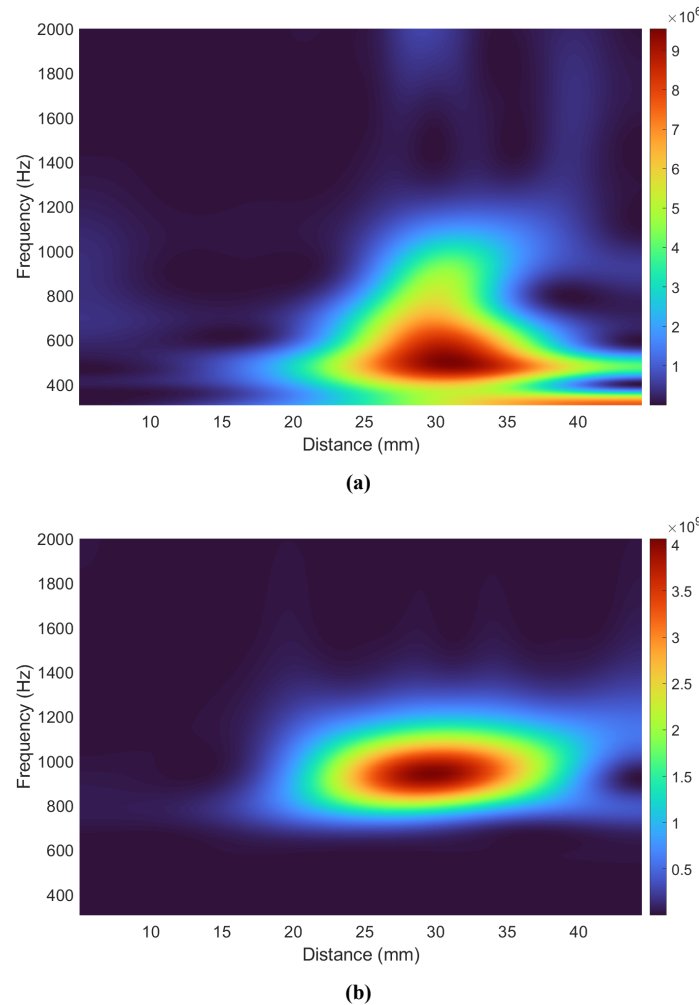


Figure 4.4: WPSs of the ABA signals (processed using the CWT) at 16 km/h: (a) Measured ABA; (b) Simulated ABA.

The simulated and measured ABA signals were then processed using the SSWT, and the results are presented in Figure 4.5. As mentioned in Chapter 3, the SSWT enhances the prominence of dominant frequency bands. For the measured ABA signal, two distinct frequency bands can be observed: one around 450 Hz and the other around 1 kHz. The 1 kHz band is consistent with that in the simulated ABA. According to Table 3.1, this dominant frequency can be induced by the first vertical bending mode of the sleepers of V-Track. The 450 Hz band is close to the full track resonance frequency of V-Track test rig, indicating that the main difference between the experimental and simulated ABA responses lies in the strength of the full track resonance.

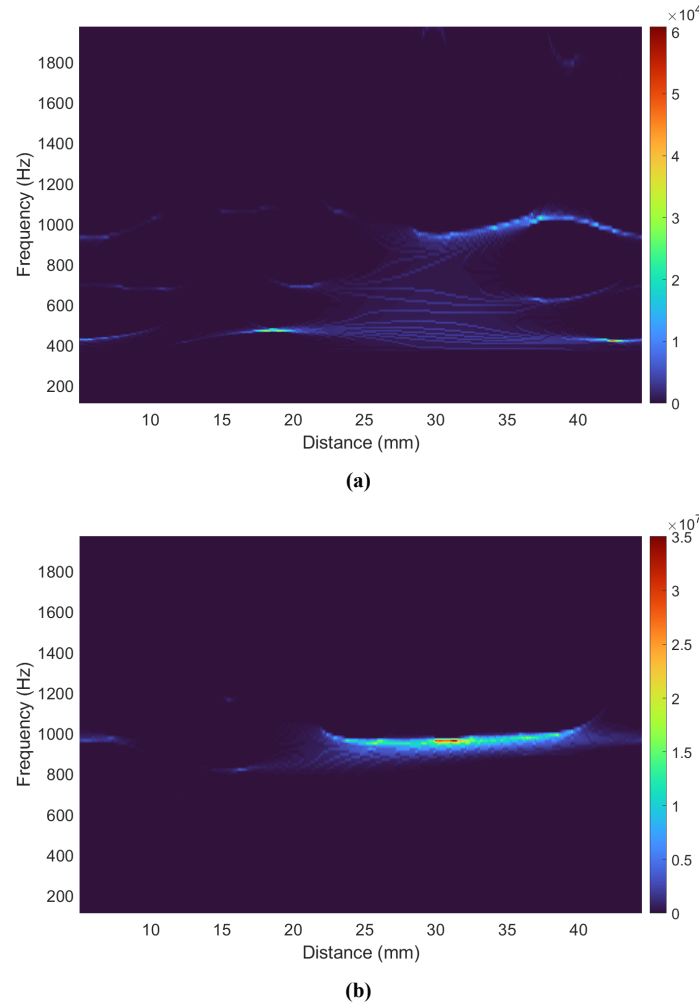


Figure 4.5: WPSs of the ABA signals (processed using the SSWT) at 16 km/h: (a) Measured ABA; (b) Simulated ABA.

A dominant frequency around 450 Hz was, in fact, also reproduced in the simulated ABA signal, which can, however, hardly be observed in the time-frequency domain results shown in Figure 4.4 and Figure 4.5, because its energy is relatively low. To more intuitively analyse the contribution of each frequency component, the local wavelet power spectrum (LWPS) can be used, as shown in Figure 4.6. A peak around 450 Hz emerges corresponding

to the full track resonance, although its power is weak.

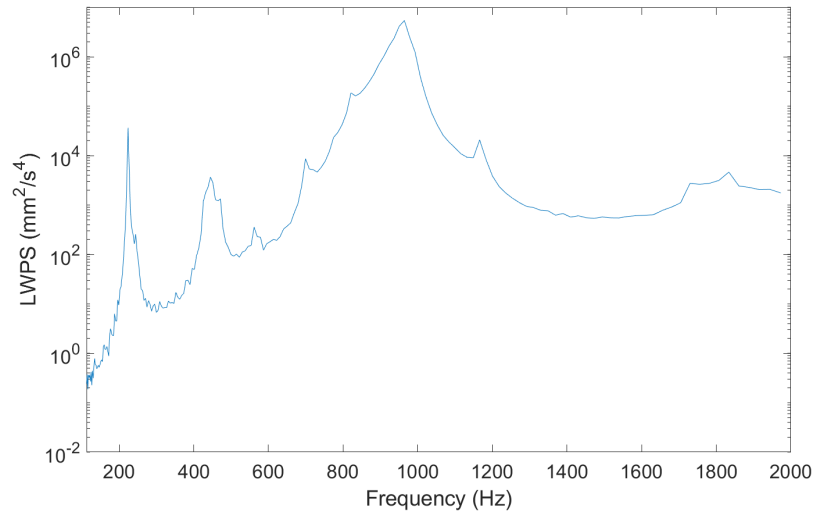


Figure 4.6: LWPS of the simulated vertical ABA (processed using the SSWT) at 16 km/h.

The main reason accounting for this discrepancy of vibration energy at 450 Hz between the simulation and experiment may be attributed to the following factor: rail surface irregularities, such as rolling contact fatigue (RCF) and corrugation, which were present in the experiment but not accounted for in the simulation. These irregularities can introduce additional excitations in the wheel–rail interactions, which in turn contributes to the measured ABA responses. Consequently, the experimental signal captures more complex dynamic behaviour than the idealised simulation. This can be further demonstrated in Figure 4.5a that the vibration energy band at about 450 Hz is present not only during the impact, but all through the rolling distance of concern in the experiment.

In summary, the developed 3D FE model demonstrates the capability in capturing flat-induced dynamic responses. Both the measured and simulated ABA signals show energy concentration around 450 Hz (although less pronounced in the simulation) and a prominent peak near 1 kHz at the impact location. This agreement confirms the effectiveness of the FE model in reproducing the key characteristics of wheel–rail impact dynamics. Therefore, the validated model can be applied in subsequent analyses involving higher rolling speeds and varying flat geometries.

5

Effects of Speed

After validation, the FE model was used for the parametric study. When using ABA to detect wheel/rail defects, the operational speed of the vehicle has a significant impact [12]. In the experiment, the wheel speed of the V-Track test rig was limited to 16 km/h, which is relatively low compared to the real-life train operational speed. To investigate the effects of the speed, this study conducted simulations with speeds ranging from 12 km/h to 100 km/h. Such a wide speed range may provide an overview of how different speeds affect the flat-induced wheel–rail impact interactions, including both the contact force and ABA signals. In this Chapter, the wheel geometry of Case 2 shown in Table 1, which corresponds to the real flat, was used in the simulations, with the speed being the only varying parameter. The low-speed range is defined as 0–50 km/h, while the high-speed range is 50–100 km/h.

5.1. Effects of Speed on Impact Force

For the contact force response, the time-domain signal allows the extraction of the maximum wheel–rail impact force and the extent of contact loss. The time histories of the wheel–rail vertical contact force with respect to rolling distance are compared in Figure 5.1 for six different speed cases: 16 km/h, 32 km/h, 45 km/h, 60 km/h, 80 km/h, and 100 km/h. The horizontal axis represents the rolling distance. We may see that, as the speed increases, both the first unloading and the impact force increase markedly. Under these conditions, the peak impact force can approach twice the steady-state contact force. It is also evident that, with a fixed flat size (Case 2), the position of the contact loss (first unloading) remains constant at approximately 15 mm, regardless of speed. However, the position of the first impact contact shifts progressively rearward as the rolling speed increases, indicating that the location of the impact is influenced by the rolling speed. Different impact locations correspond to different contact points on the wheel, which can affect the wheel–rail impact behaviour. It is worth noting that at 16 km/h, the maximum contact force occurred at not the first, but second impact, while at 60 km/h and 100 km/h, the maximum forces occurred both at their first impacts.

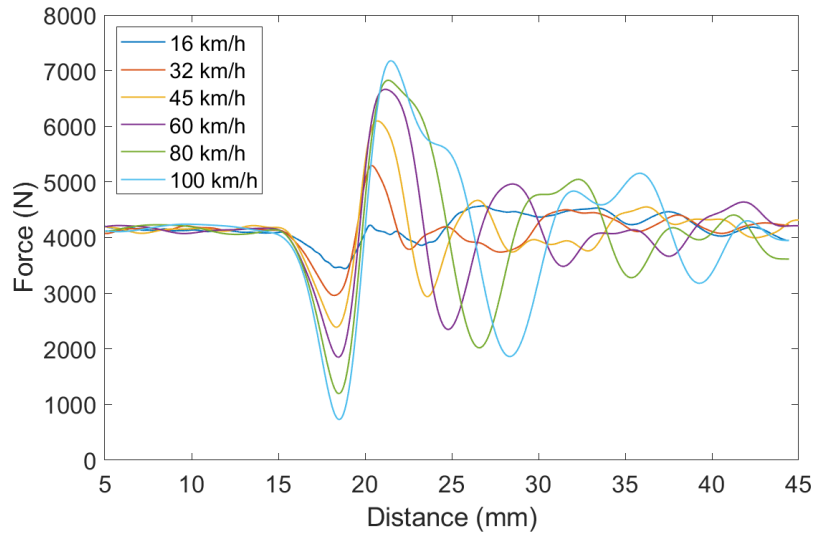


Figure 5.1: Time histories of the simulated contact force at different speeds for Case 2.

To explain the abnormal variation in contact force at 16 km/h, the vertical motions of both the rail and the wheel are analysed. The vertical displacement is shown in Figure 5.2. When the wheel rolls into the flat area and comes into contact with the rail surface, the contact force decreases due to the partial loss of the indentation, as shown in Figure 5.3. As a result of its structural stiffness, the rail moves upward, as shown in Figure 5.2, while the wheel moves downward. In other words, the trajectory of the wheel centre shifts downward due to the geometric irregularity on the tread caused by the flat. At this moment, the first impact occurs, although it is relatively weak. After the impact, the rail is forced to move downward and reaches its lowest point earlier. Meanwhile, due to large inertia, the wheel continues to move downward, resulting in a sharp increase in indentation and ultimately leading to a large contact force.

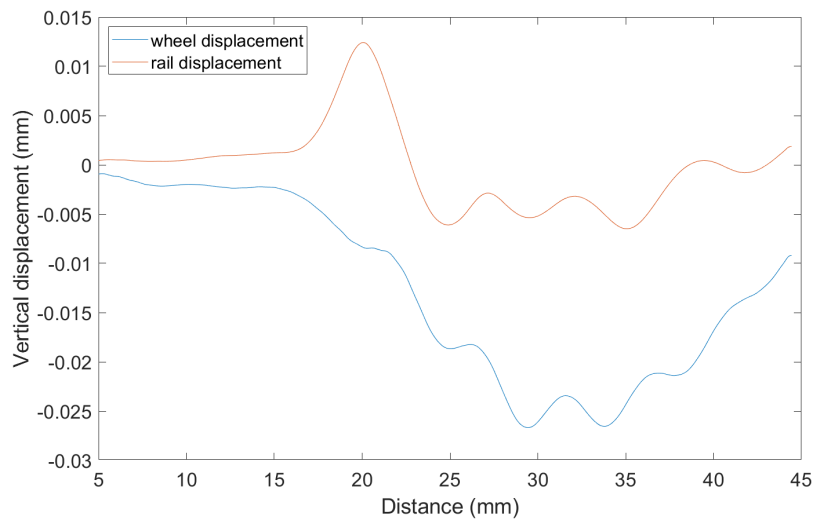


Figure 5.2: The simulated vertical displacement at 16 km/h in Case 2.

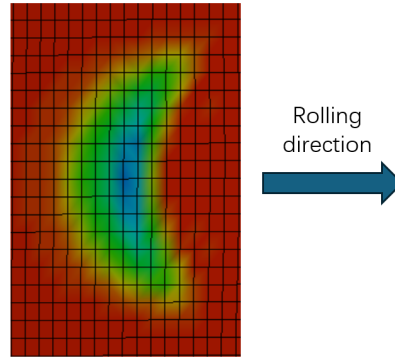


Figure 5.3: The stress at the transition region (Case 2).

The variations of the impact force (at the first impact), together with the contact loss described by (5.1), with speed are shown in Figure 5.4. It can be observed that both the impact force and the contact loss increase with rolling speed, which is consistent with expectations. At a speed of 100 km/h, most of the contact between the wheel and rail is lost. The large impact force induced by high speed further increases the risk of damage to both the rail and the wheel, which may pose a threat to the safety of the railway system and result in increased maintenance costs. It is noteworthy that once the speed exceeds 50 km/h, the rate of increase in impact force begins to decline. Similar findings have also been reported in previous studies on wheel flats, although there are some differences in the local growth trends and the specific speed ranges considered [3][5][17][51][52][53]. It can be inferred that within the typical operating speed range, the impact force exhibits local peaks.

$$CL = 1 - \frac{F_{\min}}{\bar{F}_{\text{ref}}} \quad (5.1)$$

where CL is the contact-loss ratio (dimensionless), $F_{\min}$ is the minimum filtered normal contact force; and $\bar{F}_{\text{ref}}$ is the mean filtered contact force in the steady state.

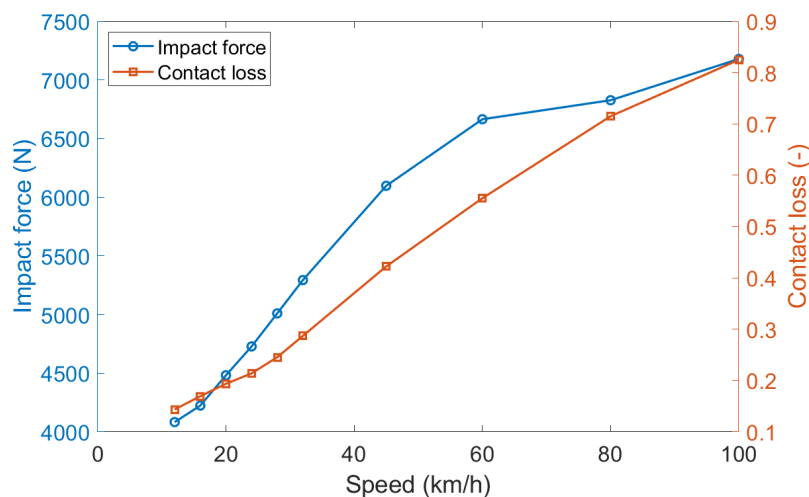


Figure 5.4: The effect of rolling speed on the impact force amplitude and the contact loss (Case 2).

5.2. Effects of Speed on ABA

The analysis of ABA responses begins in the time domain. The variations of the vertical ABA with respect to the rolling distance are shown in Figure 5.5 for three speed cases, ranging from 16 km/h to 100 km/h. It can be observed that the amplitude of the ABA increased significantly with speed, and the maximum amplitudes all occurred at the second peaks of the ABA signals. The oscillation decay following the impact can also be observed.

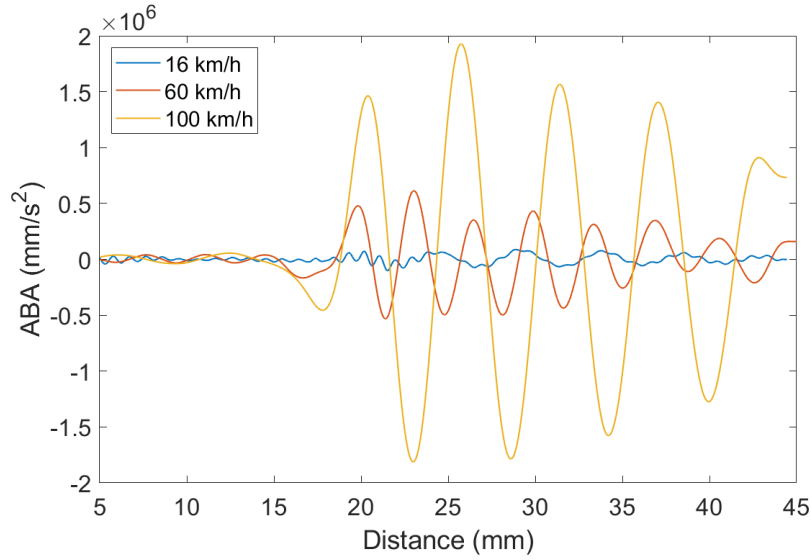


Figure 5.5: Time histories of the simulated vertical ABA at different speeds for Case 2.

To quantify the speed influences on the flat-induced ABA signal for potential monitoring applications, two indicators are used: the maximum amplitude, which corresponds to the second peak (see Figure 5.5), and the root mean square (RMS) value of the time history. The RMS is given by (5.2). These two indicators are commonly used for detecting wheel flats [15][30]. The variations of the RMS and maximum amplitude of ABA with speed are shown in Figure 5.6. The results indicate that both the RMS and the maximum amplitude of the ABA signal increase with rolling speed. However, this increase is not uniform across the speed range. In the low-speed range, the growth in both indicators is relatively gradual, while in the high-speed range, the increase becomes significantly more pronounced. This suggests that the ABA signal becomes more sensitive to wheel flats as speed increases. The enhanced sensitivity at higher speeds can be attributed to the fact that flat-induced impacts are more likely to excite high-frequency track/wheel modes, a phenomenon that is further examined in the subsequent WPS analysis.

$$\text{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N a_i^2} \quad (5.2)$$

where a is the simulated vertical ABA.

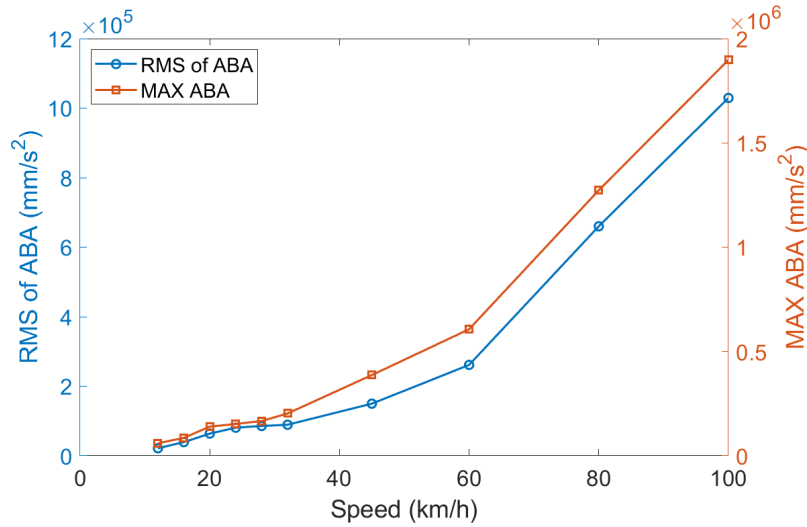


Figure 5.6: The effect of speeds on the RMS value and maximum amplitude of ABA (Case 2).

Then the CWT was used to extract the time-frequency characteristics of the simulated ABA signals. Figure 5.7 presents the WPSs of ABA at three speeds: 28 km/h, 32 km/h and 45 km/h. It shows the ABA energy was primarily concentrated in two frequency bands: about 1 kHz (as also observed in the validation speed 16 km/h in Figure 4.4 and Figure 4.5) and 5 kHz, corresponding, respectively, to the first vertical bending mode of the sleeper and a response that may involve the wheel mode (zero nodal circle, two nodal diameters), the vertical pinned–pinned resonance mode, or their combination [43].

The first signature tune is characterised by low frequency and long duration. In contrast, the second signature tune is high-frequency and short-lived, indicating that the energy is rapidly damped, likely due to the effects of components such as the primary suspension or pads.

With the increase in speed, the 1 kHz band became less dominant, and more energy shifted towards the second band. When the speed was increased to 45 km/h or higher, the 1 kHz band can be considered negligible, with the 5 kHz band being the only prominent signature tune. These findings show that the higher speed enhances the excitation of high-frequency structural modes in the wheel-rail system, resulting in the stronger ABA dynamic responses.

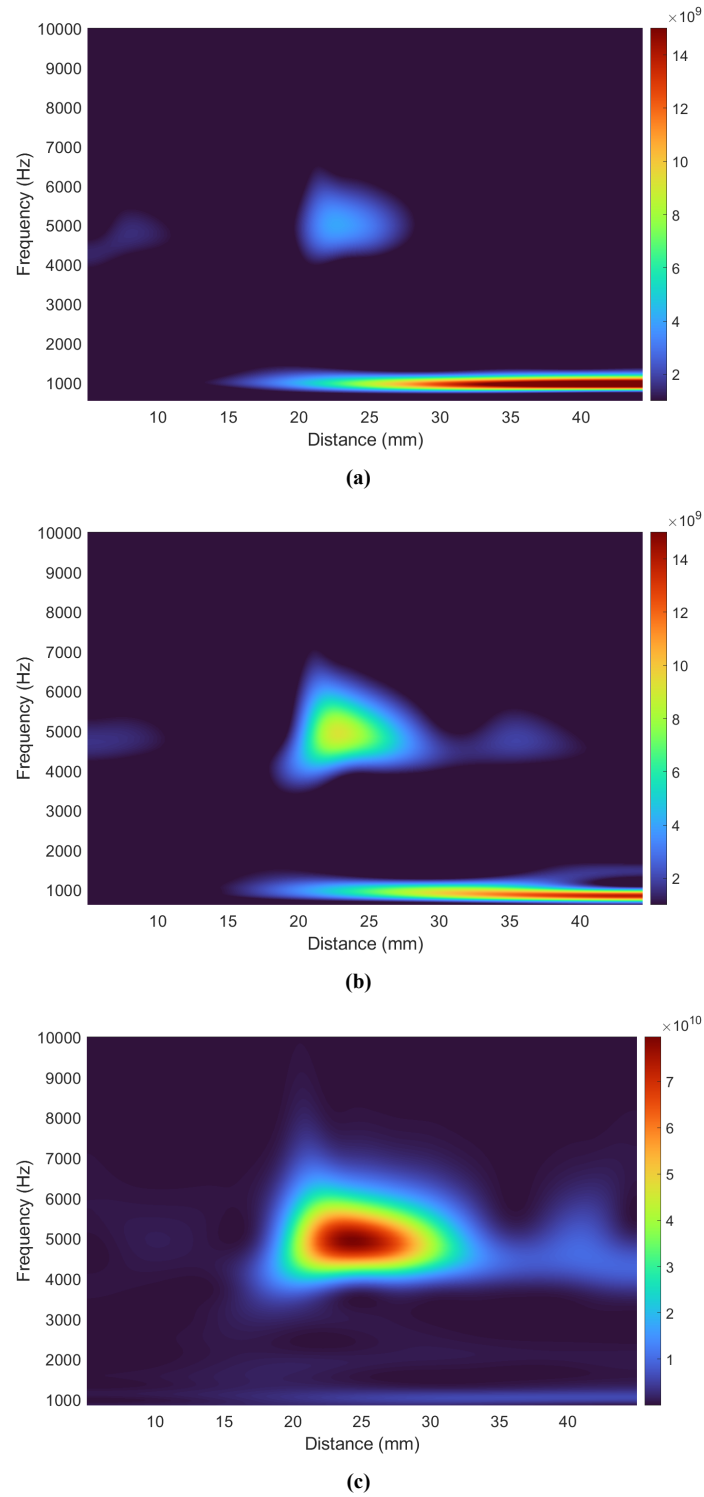


Figure 5.7: WPSs of the simulated ABA signals using the CWT for Case 2: (a) 28 km/h; (b) 32 km/h; (c) 45 km/h.

To further validate the identified signature tunes related to wheel flats, the global wavelet power spectrum (GWPS) can be employed to identify the dominant frequencies, as shown

in Figure 5.8.

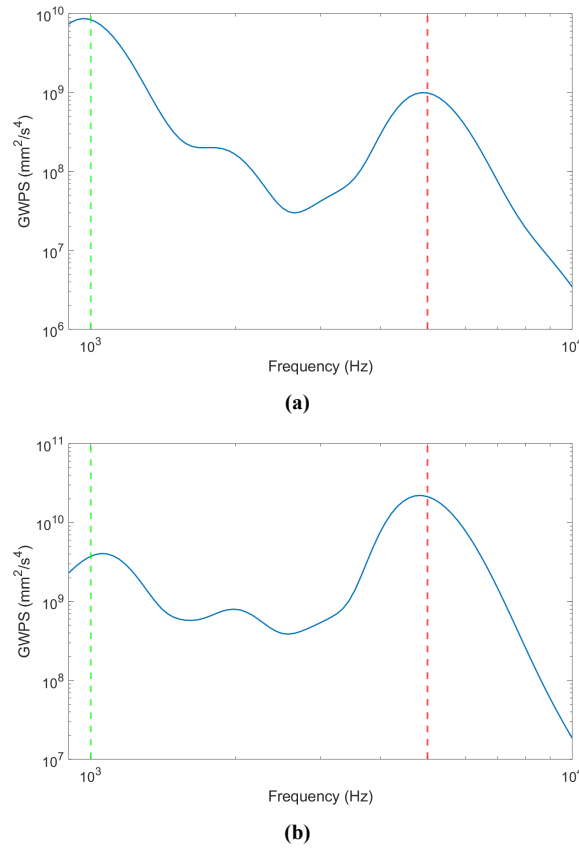


Figure 5.8: GWPSs of the simulated ABA signals using the CWT for Case 2: (a) 28 km/h; (b) 45 km/h.

Due to the short window length used, the GWPS effectively captures the dominant frequencies of the flat-induced ABA responses. The results from the GWPS analysis further confirm that the two signature tunes associated with wheel flats are located at 1 kHz and 5 kHz. From Figure 5.8, it can be observed that as the speed increases from 28 km/h to 45 km/h, the dominant frequency shifts from 1 kHz to 5 kHz. Although intermediate peaks are present, their energy is relatively low. This discontinuous transition highlights the significance of these two characteristic frequencies in the flat-induced ABA response. This finding facilitates the subsequent observation of energy variations within the characteristic scale range (frequency range).

6

Effects of Flat Length

For a wheel flat, length is a critical geometric parameter. As mentioned in chapter 2, the flat length can be used as an indicator of the severity of the wheel flat. For instance, in Italy, maintenance is required when the length of a wheel flat exceeds 40 mm [16]. For newly-formed wheel flats, the flat length may vary depending on the wheel–rail sliding conditions under which the flats are generated. Once the flat is formed, the flat depth generally remains constant in the following operation [3].

To investigate the effect of wheel flat length on the wheel-rail impact responses, the flat geometries of Case 1, Case 2, and Case 3 are selected for analyses in this chapter. The detailed geometric parameters can be found in Table 3.2. In all three cases, the wheel flats are fresh and have the same width, with the flat length ranging from 4 mm to 8 mm.

6.1. Effects of Flat Length on Impact Force

First, the time series of the simulated contact force was analysed under a fixed rolling speed with varying wheel flat lengths, as shown in Figure 6.1. At a rolling speed of 100 km/h, it can be observed that as the flat length increases, the point at which indentation begins to decrease shifts forward, while the position of the maximum impact force moves further back. This behaviour is consistent with expectations, as it is determined by the centre point of the flat region and the cylindrical shape of the wheel. At 100 km/h, two flats with a length difference of 4 mm can produce an impact force difference of approximately 1500 N, indicating that the effect of flat length is significant. Here Case 3 exhibits the highest impact force, however, this does not imply that a longer flat always results in a greater impact force, which will be further discussed in the following paragraph.

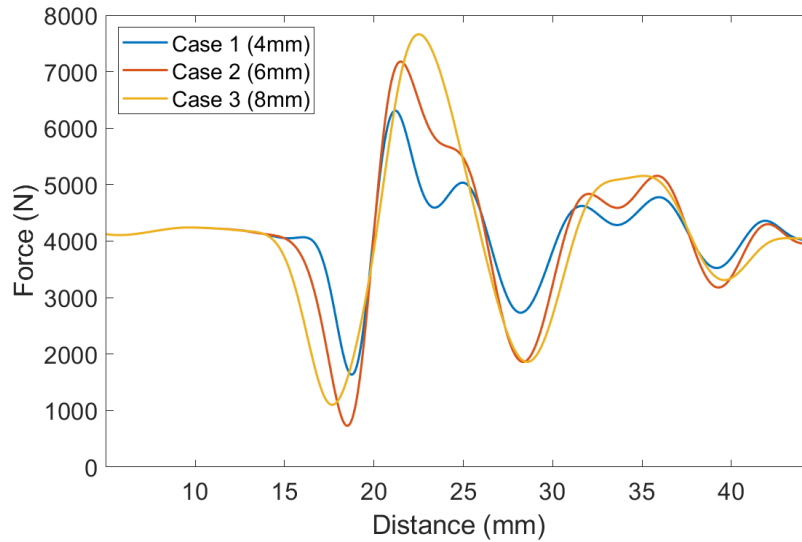


Figure 6.1: Simulated contact force time histories at 100 km/h for Cases 1–3.

The simulated impact force variations with speed for different flat lengths are shown in Figure 6.2. It can be observed that for different flat lengths, the impact forces consistently increased with speed, although the growth trends vary slightly. It is noteworthy that flat length and impact forces do not exhibit a simple positive correlation. In the low-speed range, Case 1 and Case 2 generated higher impact forces, despite having shorter flat lengths than Case 3. However, once the speed exceeded 60 km/h, a clear positive correlation between flat length and impact force emerged; that is, the impact force increased with flat length. A similar phenomenon was also observed in [54], with the prerequisite that the depth of the wheel tread defect is small, as shown in Figure 6.3. Although the flat of Size B is shorter than that of Size C, it generates a larger impact force when the rolling speed is below 150 km/h. This requires further research.

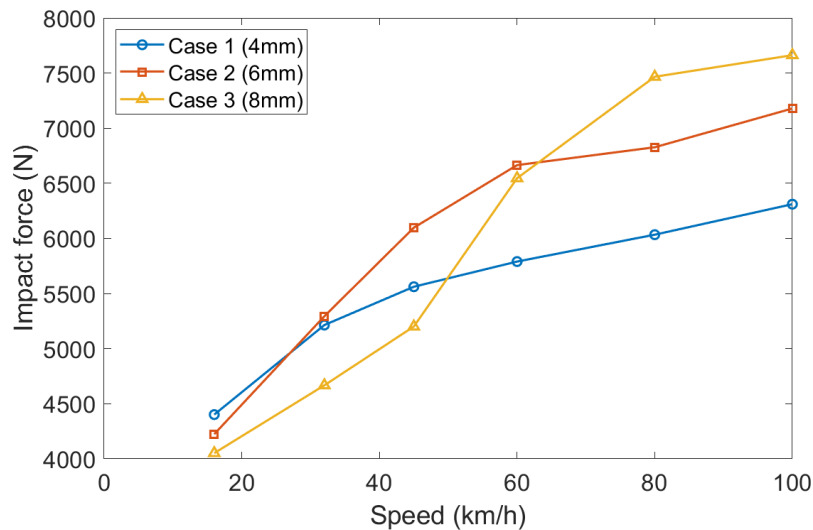


Figure 6.2: The effect of flat length on the impact force (first peak).

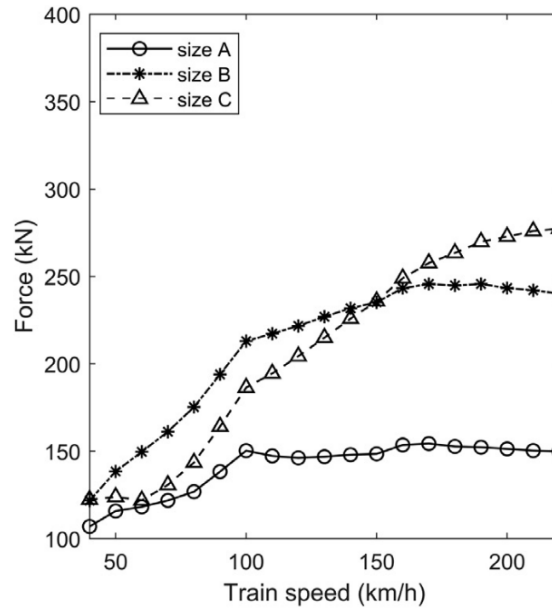


Figure 6.3: The effect of rolling speed on the impact force reported in [54].

6.2. Effects of Flat Length on ABA

The variations of the simulated vertical ABA with rolling distance is analysed, as shown in Figure 6.4. It can be observed that around 15 mm, the ABA of the three cases begins to fluctuate in sequence, corresponding to the order of their flat sizes. At 100 km/h, Case 2 has the largest ABA amplitude, despite not having the longest flat length.

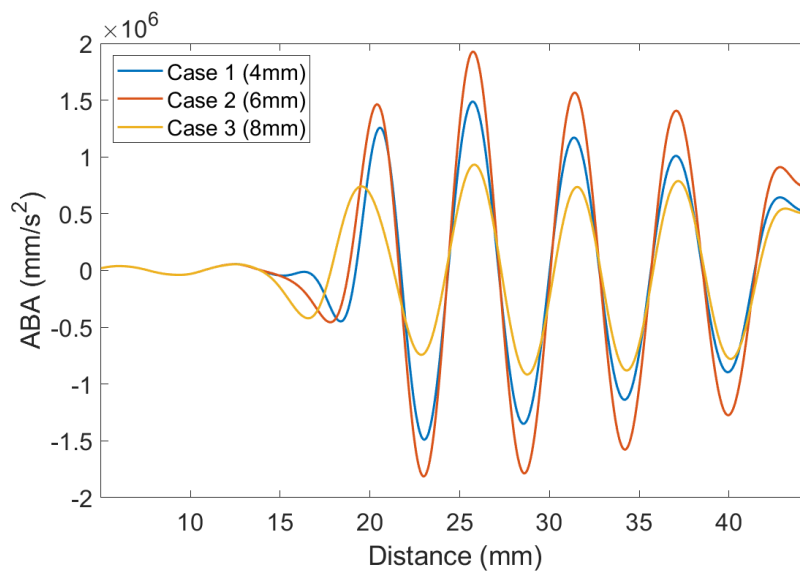


Figure 6.4: Simulated vertical ABA time histories at 100 km/h for Cases 1–3.

The RMSs of ABA of the three flat geometry cases, as a function of speed, are compared in Figure 6.5. For all three length cases, the ABA increased with speed gently in the low-speed range and the increase became more sharp at higher speeds. When the speed is below 32 km/h, the ABA responses to the wheel flats with different length are close in magnitude. As the speed increased over 40 km/h, the longest wheel flat (Case 3) generated the smallest RMS of ABA among the three. The RMS results of Case 1 and Case 2 are similar below 80 km/h, but under a wheel speed of 100 km/h, the ABA of Case 2 increased more significantly.

This is because, at 100 km/h (i.e. 28 m/s), the wheel flat of Case 2 with a length of 6 mm generated an excitation force with dominant frequency of about 5 kHz ($\approx 28/0.006$), which matched and thus intensified the 5 kHz energy bands observed in the ABA responses. In a wheel–rail system, if a wave has a wavelength λ and the rolling speed is V , then the frequency f of the resulting sinusoidal vibrations is given by [55]:

$$f = \frac{V}{\lambda} \quad (6.1)$$

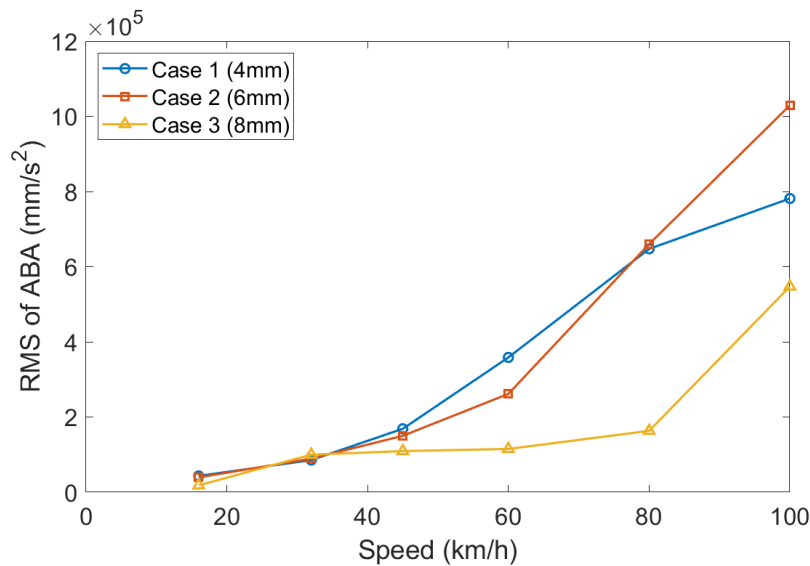


Figure 6.5: The effect of flat lengths on the RMS of ABA.

To further analyse the effect of wheel flat length on the ABA response, the CWT was applied to the ABA signals at 100 km/h to obtain the WPSs, as shown in Figure 6.6. It can be observed that for all three cases, the energy is mainly concentrated at the 5 kHz band, corresponding to the second major characteristic frequency of ABA. Among them, Case 2 shows the strongest WPS response, followed by Case 1, while Case 3 shows the weakest response. This order is consistent with the RMS values of ABA. As mentioned there, at a speed of 100 km/h, the wheel flat of Case 2 strongly excited the 5 kHz mode. Similarly, at 60 km/h (i.e. 17 m/s), the short-length flat of Case 1 (4 mm) excited the same mode at around 5 kHz ($\approx 17/0.004$), resulting in the strongest response among all cases.

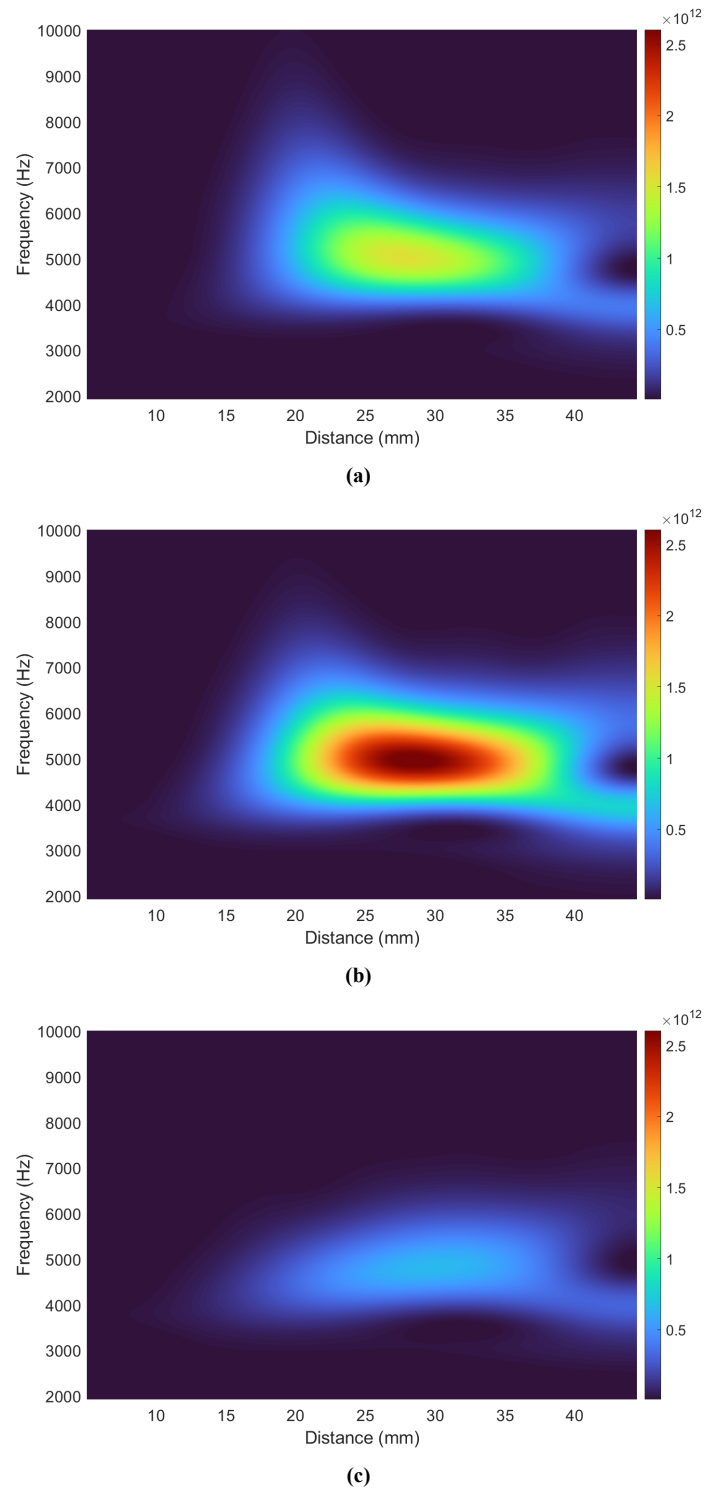


Figure 6.6: WPSs of the simulated ABA signals using the CWT at 100 km/h with different wheel lengths: (a) Case 1 (4 mm); (b) Case 2 (6 mm); (c) Case 3 (8 mm).

As mentioned in Chapter 3, the SAWP is capable of identifying how signals within specific scale ranges (frequency bands) vary over time or rolling distance, as shown in Figure 6.7.

It is an effective method for defect detection or feature extraction.

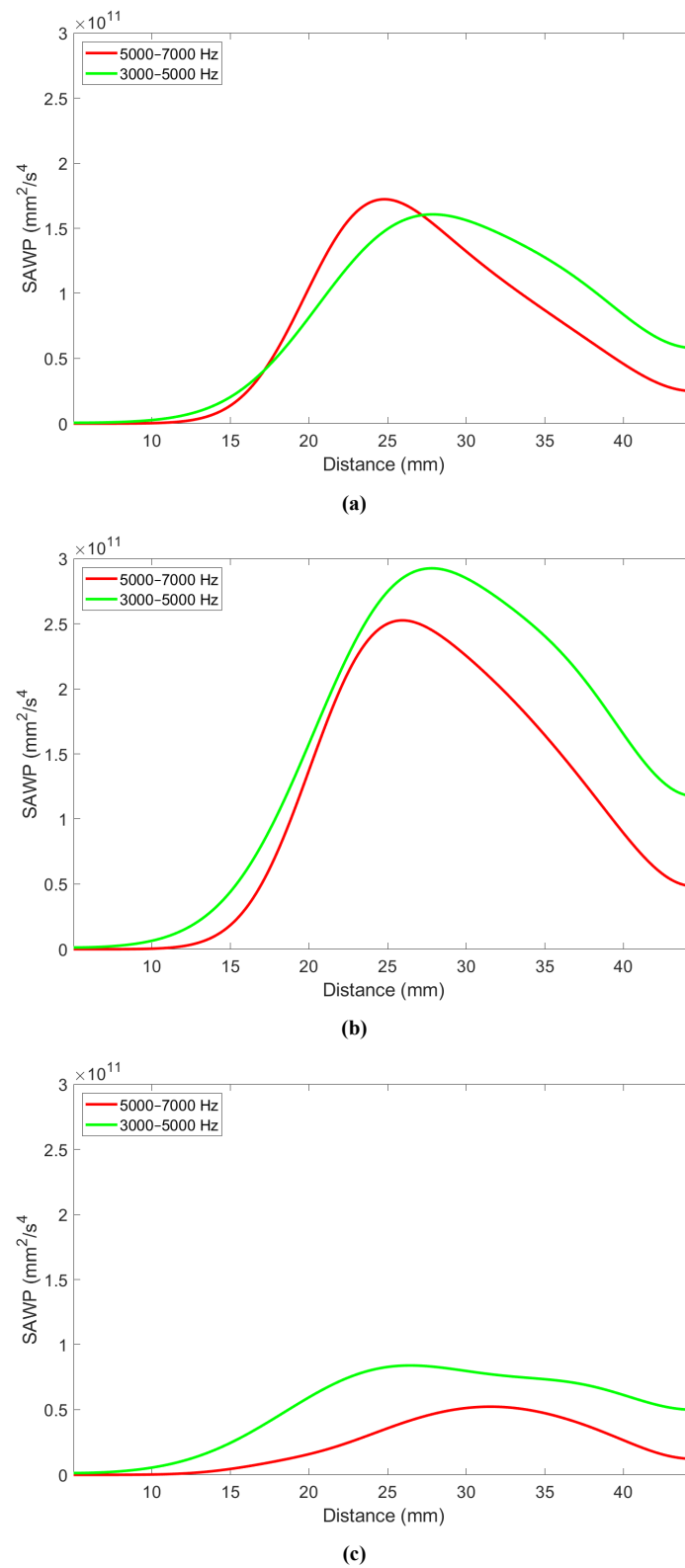


Figure 6.7: SAWPs of the simulated ABA signals using the CWT at 100 km/h with different wheel lengths: (a) Case 1 (4 mm); (b) Case 2 (6 mm); (c) Case 3 (8 mm).

Two frequency bands are used for comparison. The first band, 3000–5000 Hz, corresponds to wheel modes, such as the mode characterized by zero nodal circles and two nodal diameters. The second band, 5000–7000 Hz, corresponds to higher-order wheel modes as well as the vertical pinned–pinned resonance. Moreover, the frequency of forced vibration is also non-negligible, as it is determined by the rolling speed and the characteristic wavelength of the defect.

From Figure 6.7, it is observed that Case 2 (6 mm) exhibits the largest SAWP amplitude, followed by Case 1 (4 mm), and then Case 3 (8 mm). This order is consistent with the previous findings. Both the red curve (5000–7000 Hz) and the green curve (3000–5000 Hz) conform to this trend, indicating consistency across different frequency bands. However, the relative contribution of each band to the overall SAWP amplitude varies, reflecting differences in the underlying dynamic responses associated with the respective frequency ranges.

Taking Case 2 as an example, during the occurrence of the wheel–rail impact, both frequency bands exhibit high SAWP amplitudes, indicating that the wheel modes and the pinned–pinned resonance within these ranges are strongly excited. Moreover, the excitation frequency at this rolling speed also falls within this range, as previously mentioned. However, for Case 1, the red curve (5000–7000 Hz) shows a higher SAWP amplitude than the green curve, which is the opposite trend observed in Case 2. This suggests that the excitation induced by the shorter flat length contains higher frequency components, leading to stronger excitation of higher-order wheel modes and the pinned–pinned resonance, while the response of lower-order wheel modes is comparatively weaker. Since the lower-order wheel modes (4000–5000 Hz) play a more dominant role in influencing the ABA response, this may explain the reduced ABA amplitude observed in Case 1. Finally, for Case 3, the reason becomes evident. The longer characteristic wavelength of the wheel flat leads to an excitation containing more low-frequency components. This results in partial excitation of the lower-order wheel modes, while the higher-order wheel modes and the pinned–pinned resonance are not effectively activated. As shown in the figure, this manifests as a higher amplitude of the green curve compared to the red curve, with the green curve also reaching its peak earlier.

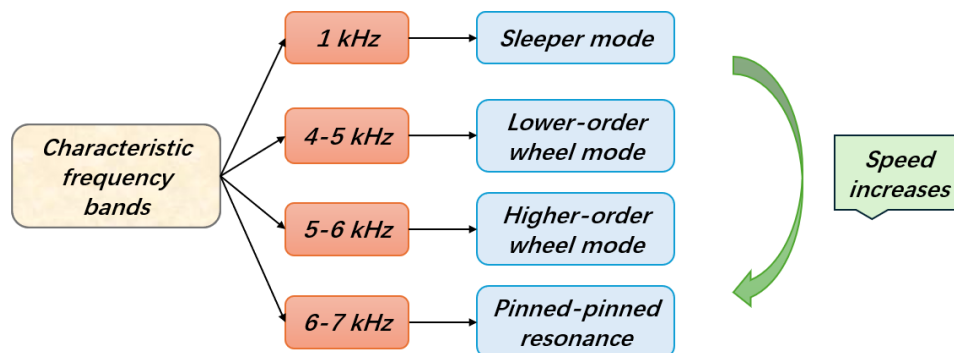


Figure 6.8: Key frequency bands.

As mentioned in Chapters 4 and 5, at speeds of 32 km/h or lower, the signature tune around 1 kHz, corresponding to the first vertical bending mode of the sleeper, can be identified. A plausible explanation for this phenomenon is that, under low-speed conditions, the excitation induced by short-wave wheel flats predominantly contains frequency components below 2 kHz, which are insufficient to excite higher-frequency modes. In this case, the intensity of the ABA response is primarily governed by the response of modes near 1 kHz.

In summary, the SAWP extracted from the CWT proves to be a valuable approach for monitoring wheel flat conditions. Nevertheless, it is important to emphasize that, under three-dimensional conditions, neither the SAWP amplitude nor the overall intensity of the ABA response exhibits a straightforward positive relationship with flat length. This observation remains valid even at high rolling speeds, where the impact force tends to increase with longer flats.

Effects of Development Stage

Once a fresh flat is formed on the wheel tread, if not addressed in time, repeated wheel-rail impact will gradually wear down the edges of the flat. Over time, this leads to the development of a longer and smoother transition region, and thus a rounded flat. As mentioned in Chapter 3, the fresh flat corresponds to the initial stage of flat development, while the rounded flat represents the mature stage.

Case 1 (fresh), Case 4 (rounded), and Case 5 (rounded) are the three cases analysed in this chapter. The detailed parameters can be found in Table 3.2, and 3D nodal coordinates can be found in Figure 3.9 to Figure 3.13. Case 4 was designed to simulate the wheel-rail impact induced by a rounded flat. The flat in Case 4 has the same maximum depth as that in Case 1. Similarly, Case 5 also shares the same maximum depth as Case 1, but its flat length is even greater than that of Case 4, representing a more developed and severely worn stage of flat evolution. This also implies a smoother variation in wheel profile curvature, with a longer transition region from the non-flatted area to the flat centre.

Table 7.1: Wheel flats at different development stages.

	Case 1	Case 4	Case 5
Type	Fresh	Rounded	Rounded
Stage	Initial	Intermediate	Mature

7.1. Effects of Development Stage on Impact Force

The influence of the wheel flat development stage on the flat-induced wheel-rail impact force is first analysed. The variation of contact force with rolling distance under the three development stages is shown in Figure 7.1. It can be observed that as the edges of the flat region undergo progressive wear, the point at which the indentation begins to decrease shifts

forward. However, the location of the contact force peak appears to remain unaffected under the rolling speed of 100 km/h.

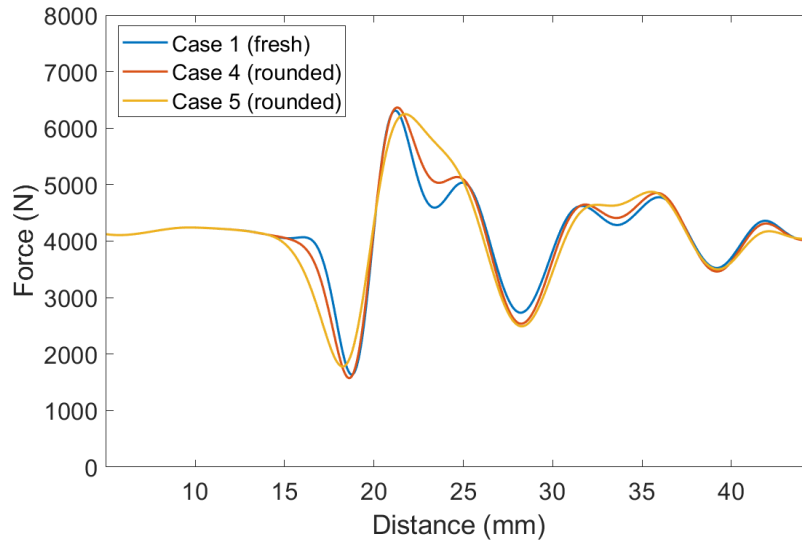


Figure 7.1: Time histories of the simulated contact force at 100 km/h for Cases 1, 4, and 5.

By comparing the impact forces generated by the fresh (Case 1) and rounded (Case 4 and Case 5) flats in Figure 7.2, it can be observed that the rounded flat does not change the overall trend of increasing impact force amplitude with speed. In addition, the impact force amplitudes of both Case 4 and Case 5 are comparable to that of Case 1 in the high-speed range (above approximately 60 km/h). This suggests that at higher rolling speeds, the peak impact force is primarily governed by the maximum flat depth, regardless of the flat length. When the speed is below 50 km/h, the rounded flat effectively reduces the impact force peak, as the smooth variation in the curvature of the wheel profile may play a role.

Moreover, as the rolling speed increases, the impact force in Case 4 converges to that of Case 1 at a lower speed compared to Case 5. This indicates that, with the same maximum depth, a more developed (i.e., longer) wheel flat in the mature stage requires a higher speed to generate an impact force close to that of the initial stage. In other words, the impact force response is weakened.

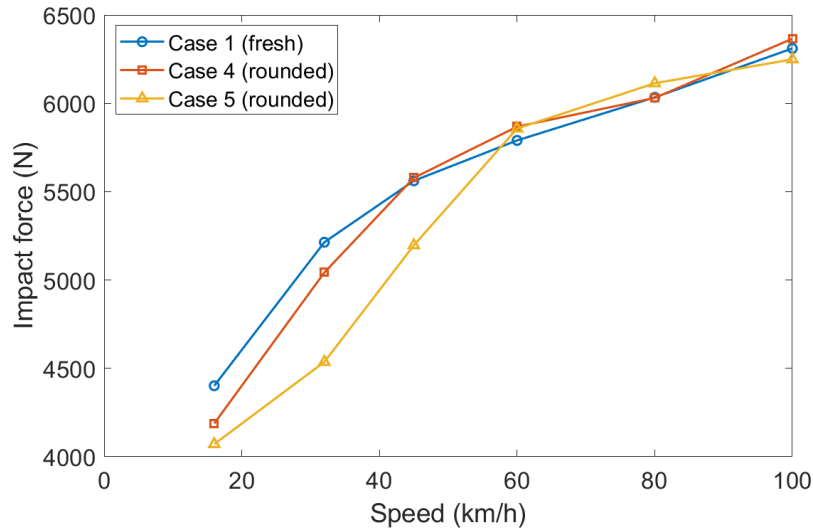


Figure 7.2: The variations of impact force amplitude with speed induced by flats at different development stages.

7.2. Effects of Development Stage on ABA

Then the effect of the wheel flat development stage on the ABA response is examined. The variation of the simulated vertical ABA with rolling distance at a speed of 80 km/h is analysed, as shown in Figure 7.3. In all three cases, the maximum ABA amplitude appears at the second peak, and its magnitude decreases with the progression of the development stage. At this rolling speed, the oscillatory decay of the ABA signal is clearly observed.

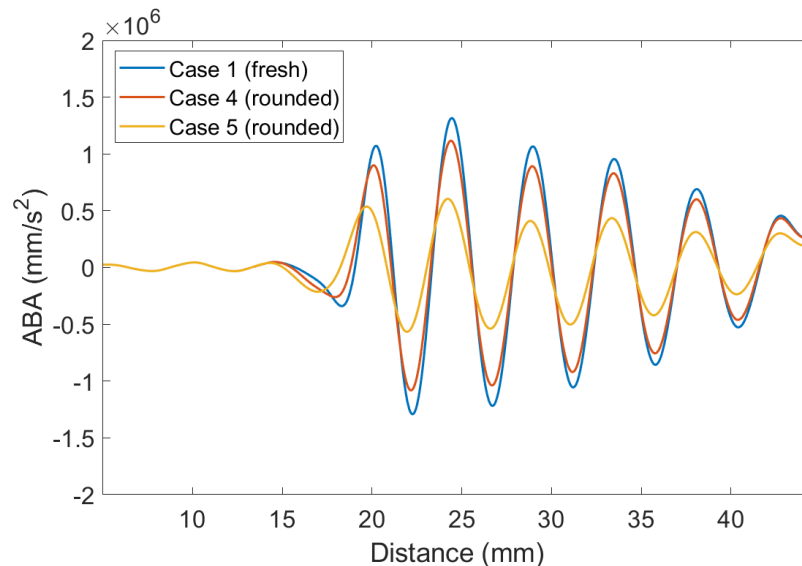


Figure 7.3: Time histories of the simulated vertical ABA at 80 km/h for Cases 1, 4, and 5.

In order to provide a more robust measure of ABA fluctuation across different cases, the RMS of the ABA signal is evaluated. The RMS of ABA obtained with Case 5 (rounded flat) remains lower than that of Case 1 (fresh flat) throughout the entire speed range, as shown in Figure 7.4. Case 4 also exhibits a generally lower RMS value compared to Case 1, although the two become comparable at 100 km/h.

With the maximum depth remaining unchanged, the longer length of the rounded flat may reduce high-frequency excitation, resulting a weaker dynamic response or structural resonance, provided that the speed is below 100 km/h. This indicates that the development of wheel flat from fresh to worn may reduce the ABA response (RMS).

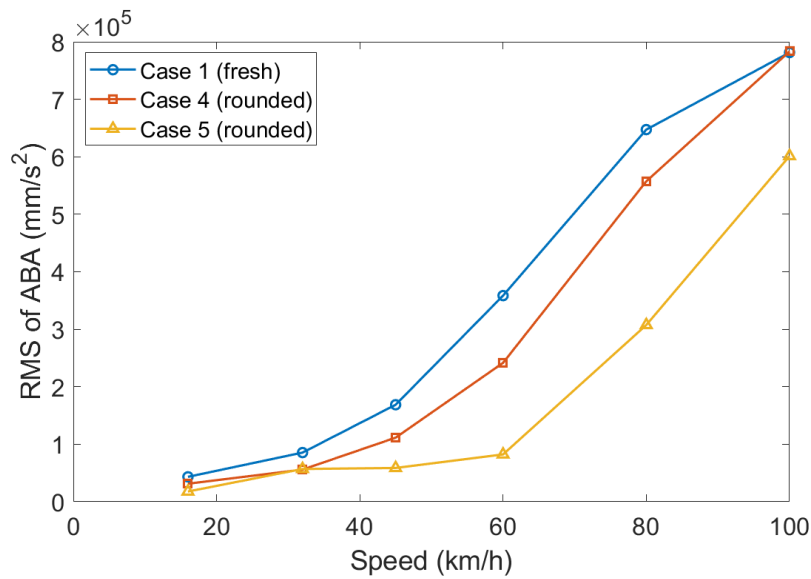


Figure 7.4: The variations of the RMS of ABA induced by flats at different development stages.

After the analysis of the RMS, the ABA signals of Case 5 (rounded) at 32 km/h and 45 km/h were processed using the CWT, and the results are shown in Figure 7.5. At 32 km/h, the vibration energy was concentrated around the two major characteristic frequencies, with the 1 kHz band response being dominant and the 5 kHz band response comparatively weak. When the speed increased to 45 km/h, more vibration energy was concentrated around the second major characteristic frequency, consistent with the behaviour observed in the fresh-flat cases (Chapter 5). Figure 7.5c presents the WPS of ABA obtained with the fresh flat (case 1) at 45 km/h. By comparison, it can be observed that at 45 km/h, the fresh flat induced a stronger ABA response at the 5 kHz characteristic frequency. This confirms the results presented in Figure 7.4.

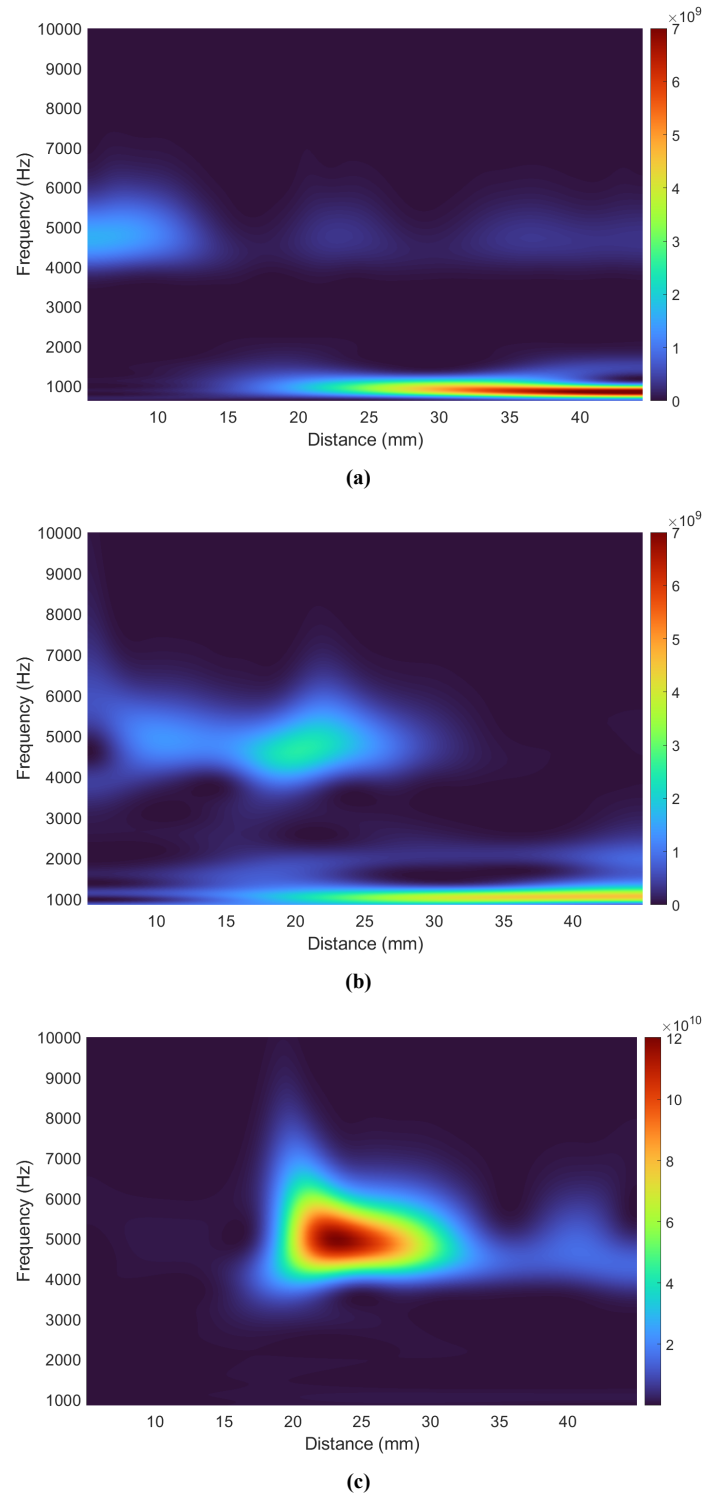


Figure 7.5: WPSs of the simulated ABA induced by fresh and rounded flats: (a) Case 5 (rounded) at 32 km/h; (b) Case 5 (rounded) at 45 km/h; (c) Case 1 (fresh) at 45 km/h.

For Case 1, Case 4, and Case 5, the flat length increases progressively. At a speed of 100 km/h, Case 1, having the shortest length, effectively excites higher-order wheel modes and

the pinned–pinned resonance. Although the flat in Case 4 is longer, it can also effectively excite these flat-related modes, as the signature tune spans a frequency range rather than a single frequency. Consequently, the ABA response intensity of Case 1 and Case 4 becomes comparable at 100 km/h, as shown in Figure 7.6. In Case 5, the flat is too long to effectively excite the second signature tune, resulting in a significantly lower SAWP compared to the other two cases. The selected frequency range of 4000–6000 Hz encompasses multiple modes that are associated with the flat-induced impact response.

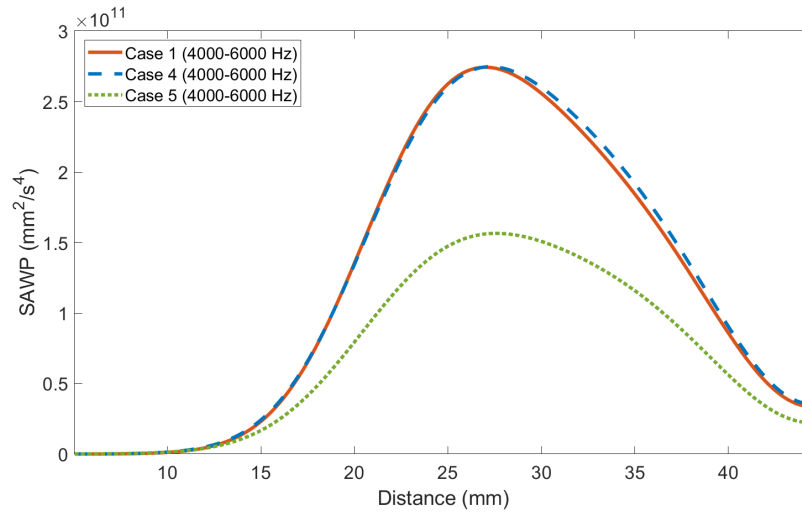


Figure 7.6: SAWPs of the simulated ABA signals using the CWT at 100 km/h with different flat development stages: Case 1 (fresh); Case 4 (rounded); Case 5 (rounded).

In summary, wheel flats at different development stages correspond to varying degrees of edge wear, which in turn alter the length of the defect. At the same rolling speed, severely worn flats with longer flat lengths may fail to effectively excite wheel or track modes located within the signature tunes, potentially resulting in a weaker ABA response compared to fresh flats. However, when the rolling speed is sufficiently high, even rounded flats can induce significant SAWP amplitudes, as illustrated in Figure 7.6.

Conclusions and Recommendations

This chapter presents the conclusions and recommendations. It addresses the research questions proposed in the introduction and summarizes the effects of wheel rolling speed, flat length, and development stage on two types of impact responses: impact force and ABA responses. In addition, signature tunes associated with wheel flats were extracted through signal processing techniques, and the relationship between wheel flat properties and monitoring indicators was critically discussed. Based on these findings, potential directions for future research are proposed to further support the development of wheel monitoring using ABA systems.

8.1. Conclusions

This study employed a 3D explicit FE model to simulate wheel-rail impact contact induced by wheel flats and conducted a comprehensive parametric study. To address the first sub-question of this study, the effect of speed on the impact responses induced by wheel flats was examined first. The results indicate that as speed increases, the wheel-rail impact force at the first impact grows continuously and non-linearly, with the growth rate slowing beyond 50 km/h. Based on the time-frequency analysis of ABA responses at different speeds, two major characteristic frequencies, also referred to as signature tunes shown in Figure 8.1, are identified in the ABA responses induced by flats: one at about 1 kHz, corresponding to the sleeper's first vertical bending mode, and the other at about 5 kHz, associated with the wheel modes (e.g., zero nodal circle and two nodal diameters), and the potential pinned-pinned resonance. As speed increases, the ABA response at the 5 kHz band becomes increasingly dominant. Further investigation indicates that, under low speed (< 32 km/h) conditions, the ABA results are not sensitive to the wheel flat length; and with a high speed (> 50 km/h), the excitation force with a dominant frequency that depends on wheel speed and flat length may strongly affect the ABA intensity.

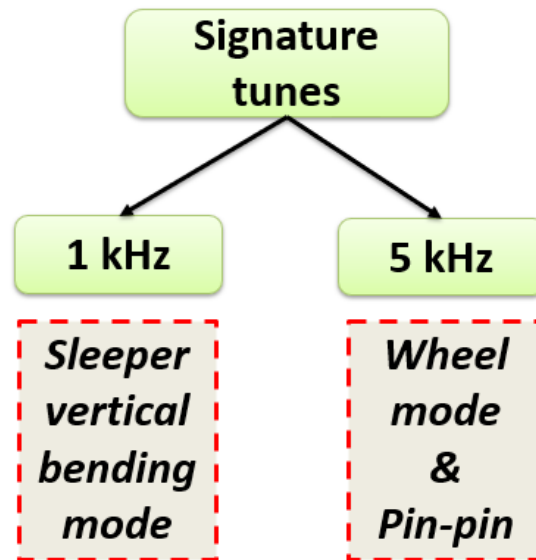


Figure 8.1: Signature tunes of wheel flats.

Then the effect of flat length on the impact responses was examined. Regarding the impact force response, in the high-speed range, the impact force shows a positive correlation with flat length, which is consistent with previous research findings. However, in the low-speed range, shorter flats may generate greater impact forces. This phenomenon requires further investigation to clarify the underlying mechanisms. The effect of flat length on the ABA responses, however, is more complex. The flat length, in combination with the wheel rolling speed, influences the flat-induced ABA responses. Therefore, under fixed rolling speed conditions, a longer wheel flat does not necessarily result in a stronger ABA response, as the modes associated with the wheel flat may not be effectively excited.

Finally, the impact response induced by a rounded flat was studied, which suggests that the development of a wheel flat from fresh to worn may lead to a reduction in both the impact force amplitude at speeds below 50 km/h and the ABA response, with the maximum depth unchanged. At sufficiently high speeds, such as the typical operating speed of 100 km/h for trains, the difference in the wheel–rail impact force between a mature-stage wheel flat and a fresh flat becomes negligible.

Based on the current findings of this study, it can be concluded that multiple types of indicators are relevant for wheel flat monitoring. These include the geometric characteristics of the flat, the measured wheel–rail impact force, and both the time-domain and time–frequency responses of the ABA signal, as shown in Figure 8.2.

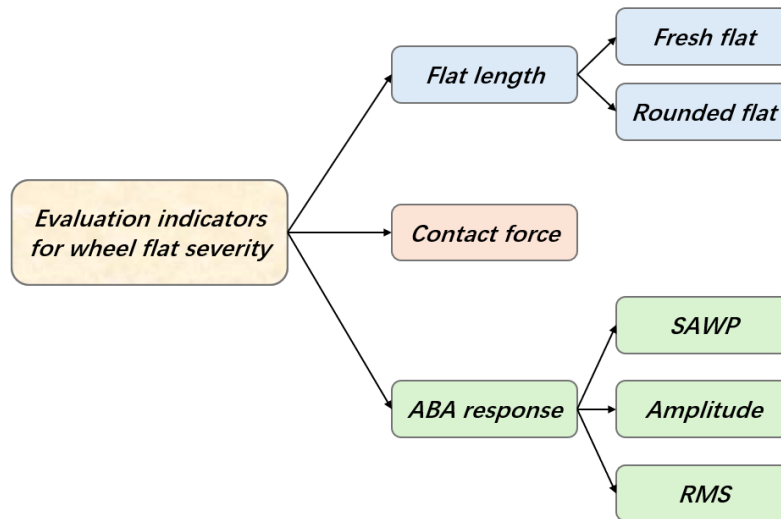


Figure 8.2: Indicators relevant to wheel flat monitoring.

If ABA system is adopted to detect the presence and evaluate the severity of wheel flats, a key problem is that currently there are no relevant standards formulated due to the complex relationships among ABA and other indicators. For example, assuming that a longer flat indicates greater severity, as discussed in Chapter 2, there are cases where a longer flat may in fact produce lower or only slightly changed impact forces, such as a fresh flat at low speeds, thereby potentially reducing the risk of wheel tread spalling or rail breakage. Furthermore, a pronounced ABA response does not necessarily indicate a long flat. The relationship varies with rolling speed, which needs future research. Therefore, at the current stage, monitoring wheel flats cannot rely solely on ABA systems; it needs to be complemented with other technologies, such as direct measurement and contact force detectors (e.g. WILD), to enable a more comprehensive assessment of wheel conditions and associated risks, thereby facilitating the development of effective maintenance strategies. However, if in the future ABA systems become sufficiently advanced to accurately reflect flat geometric parameters and impact loading, relying solely on ABA for monitoring wheel flats would be feasible. Achieving this will require more measurement and simulation data to establish precise mappings between multiple indicators. Then the second research question has been addressed.

8.2. Recommendations

A preliminary framework which shows the future work is illustrated in Figure 8.3. In the simulation stage, additional factors need to be considered, such as the location of wheel–rail impact, since an impact occurring at mid-span or directly above a sleeper can influence the responses of the system. In addition, rail surface irregularities can be incorporated, and the solution zone can be extended to simulate multiple consecutive impacts, making the model more representative of real-world conditions. Furthermore, a wider range of simulations should be conducted to cover different flat geometries and rolling speeds, thereby

generating a larger dataset to support the development of detection algorithms. The algorithm will then be experimentally validated for reliability and subsequently refined based on the experimental results. Such an approach would enable the efficient monitoring of wheel flats using ABA systems. Moreover, given the broad applicability of the ABA system, it could be extended to the comprehensive monitoring of the entire railway system, including both vehicles and tracks.

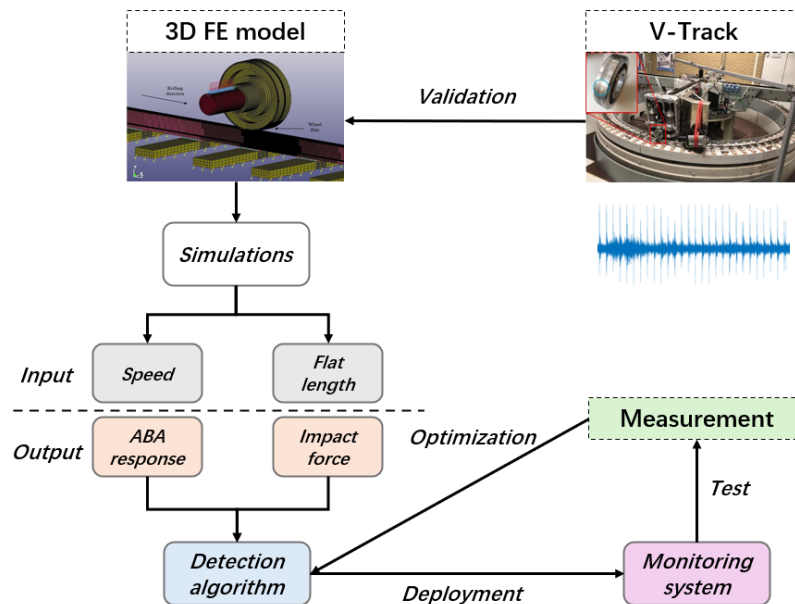


Figure 8.3: A preliminary framework for future research .

References

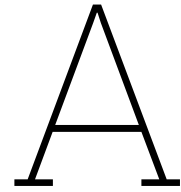
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Simulation - Case 1

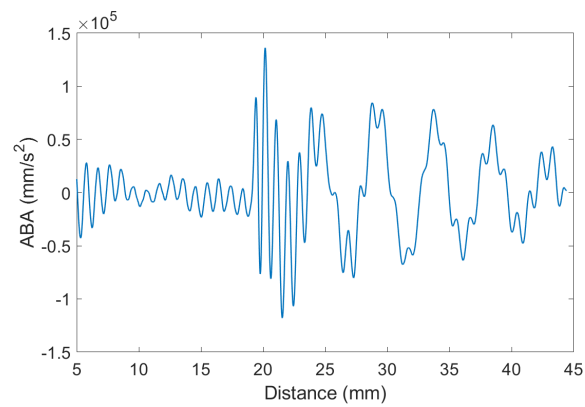


Figure A.1: The simulated ABA in Case 1 at 16 km/h.

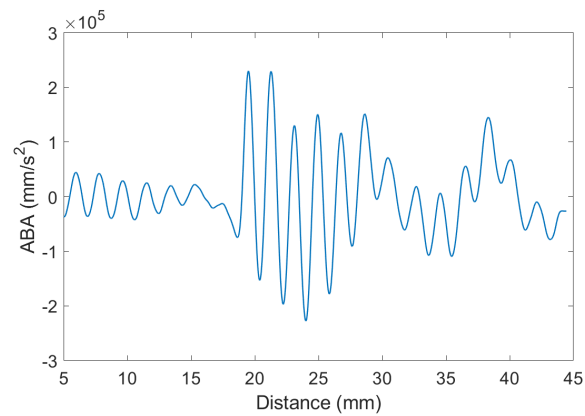


Figure A.2: The simulated ABA in Case 1 at 32 km/h.

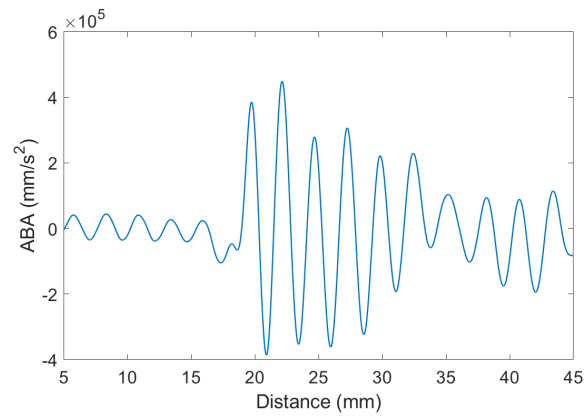


Figure A.3: The simulated ABA in Case 1 at 45 km/h.

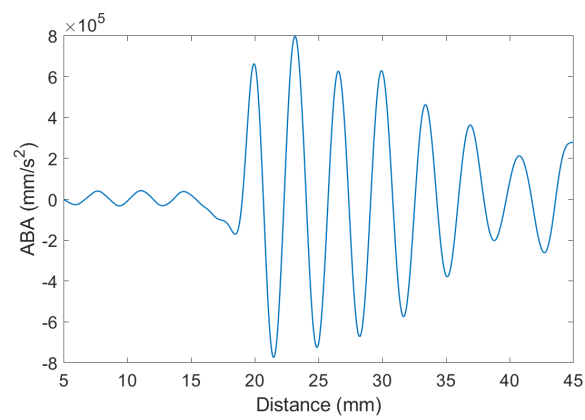


Figure A.4: The simulated ABA in Case 1 at 60 km/h.

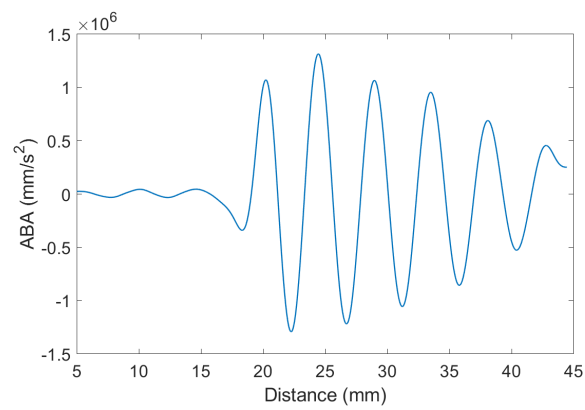


Figure A.5: The simulated ABA in Case 1 at 80 km/h.

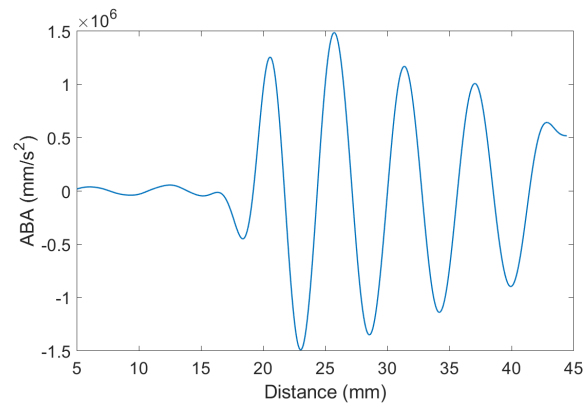


Figure A.6: The simulated ABA in Case 1 at 100 km/h.

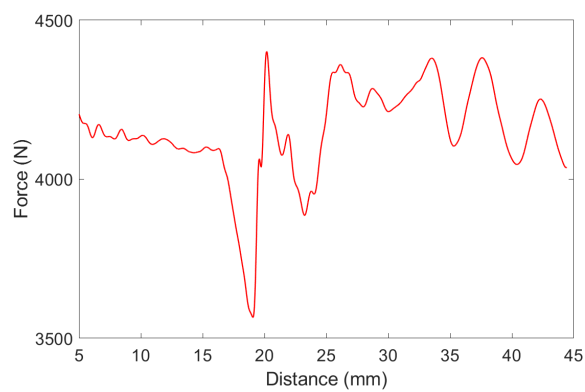


Figure A.7: The simulated contact force in Case 1 at 16 km/h.

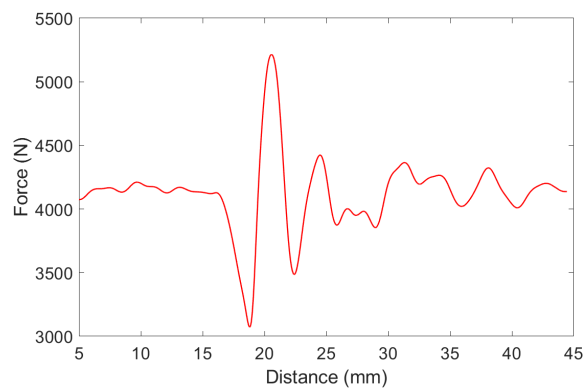


Figure A.8: The simulated contact force in Case 1 at 32 km/h.

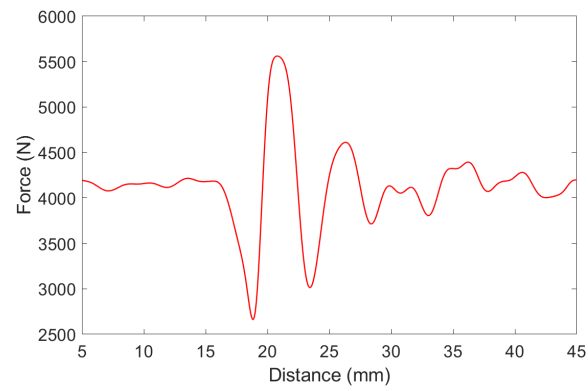


Figure A.9: The simulated contact force in Case 1 at 45 km/h.

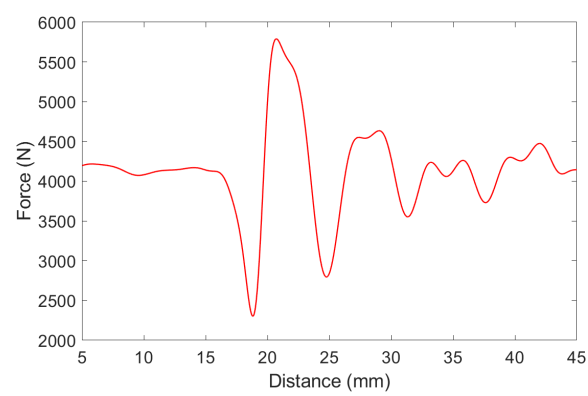


Figure A.10: The simulated contact force in Case 1 at 60 km/h.

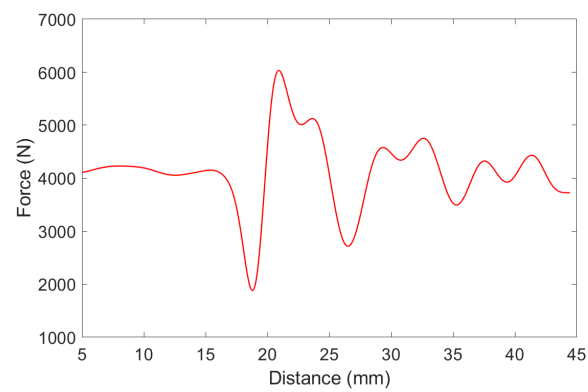


Figure A.11: The simulated contact force in Case 1 at 80 km/h.

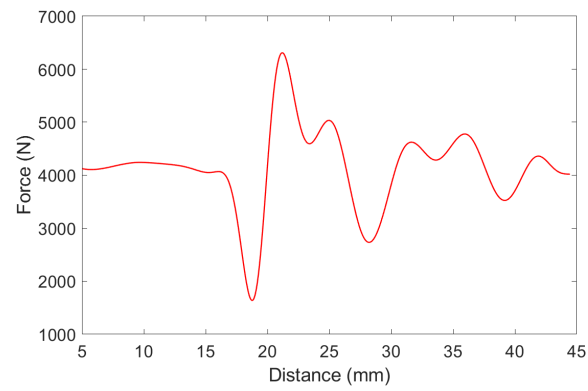


Figure A.12: The simulated contact force in Case 1 at 100 km/h.

B

Simulation - Case 2

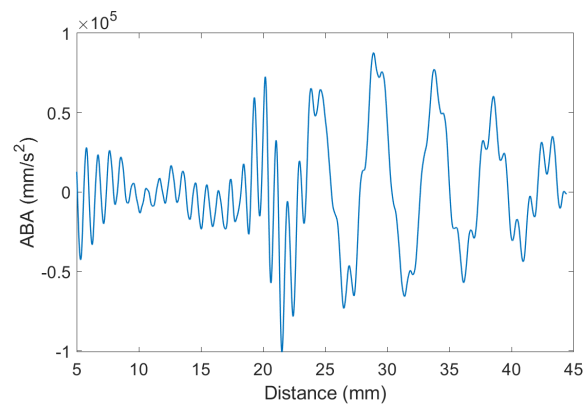


Figure B.1: The simulated ABA in Case 2 at 16 km/h.

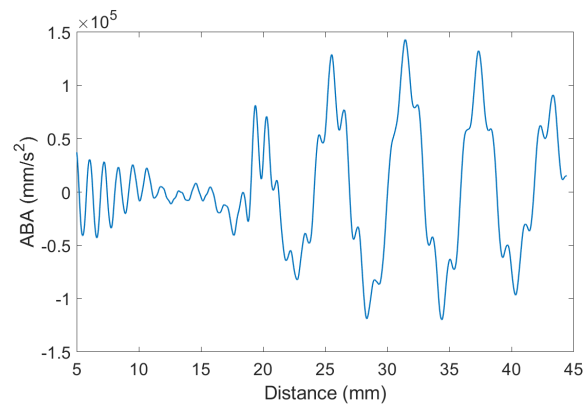


Figure B.2: The simulated ABA in Case 2 at 20 km/h.

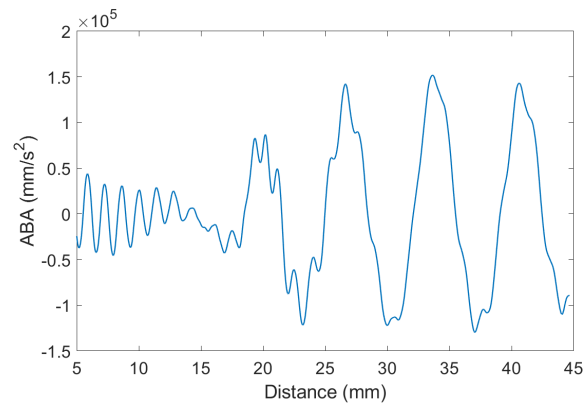


Figure B.3: The simulated ABA in Case 2 at 24 km/h.

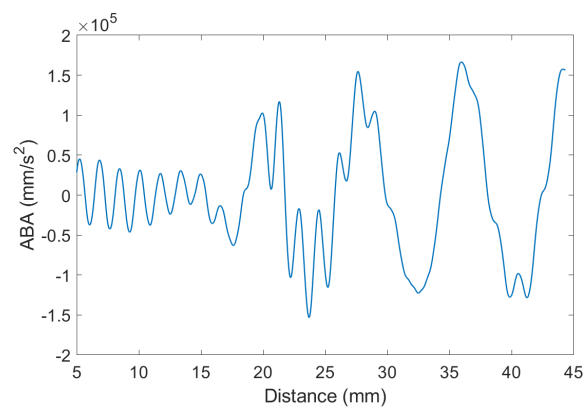


Figure B.4: The simulated ABA in Case 2 at 28 km/h.

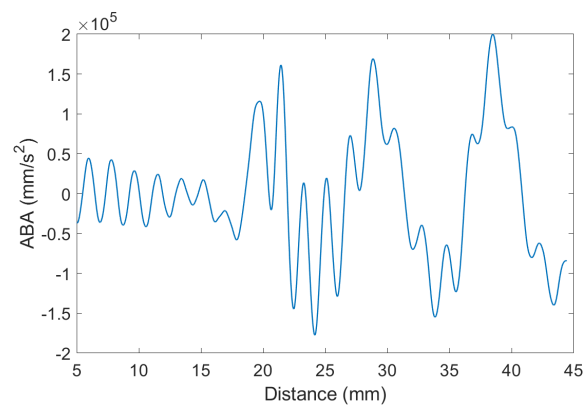


Figure B.5: The simulated ABA in Case 2 at 32 km/h.

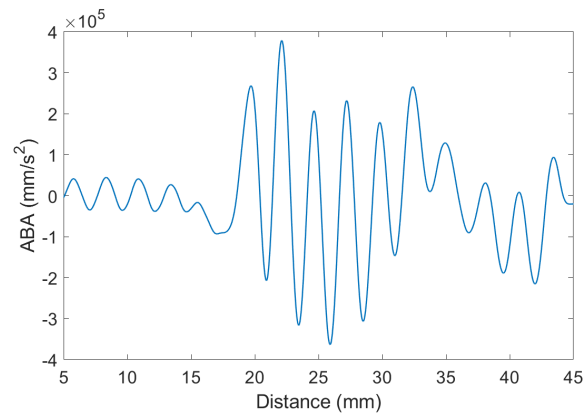


Figure B.6: The simulated ABA in Case 2 at 45 km/h.

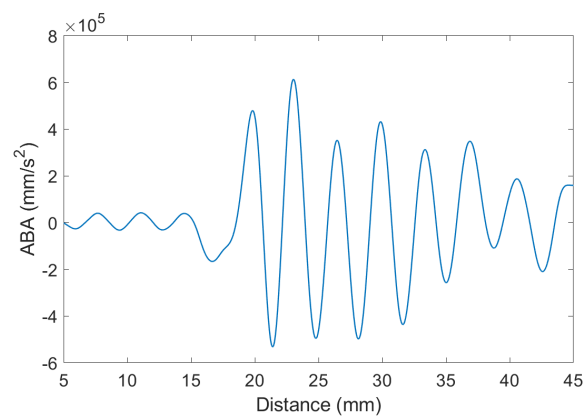


Figure B.7: The simulated ABA in Case 2 at 60 km/h.

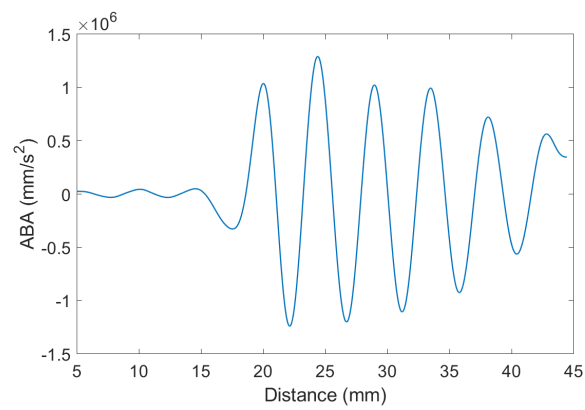


Figure B.8: The simulated ABA in Case 2 at 80 km/h.

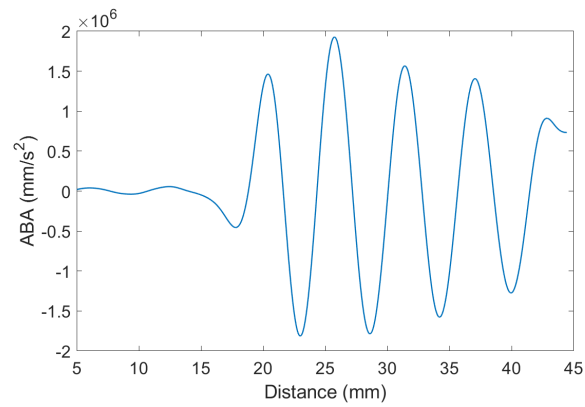


Figure B.9: The simulated ABA in Case 2 at 100 km/h.

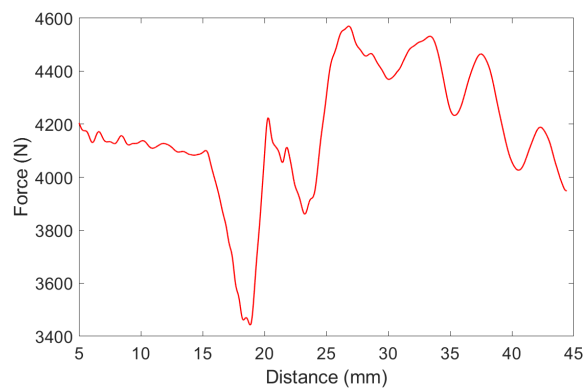


Figure B.10: The simulated contact force in Case 2 at 16 km/h.

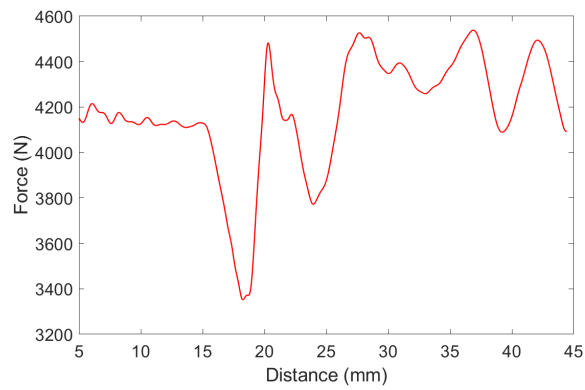


Figure B.11: The simulated contact force in Case 2 at 20 km/h.

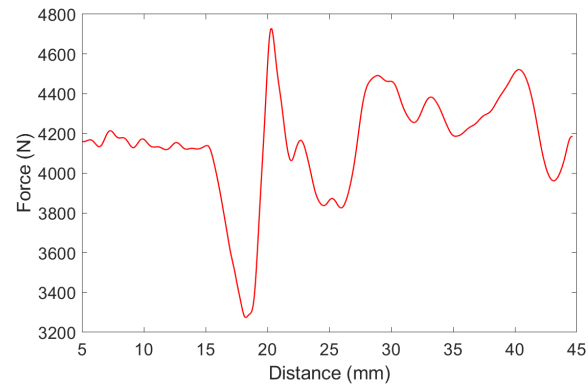


Figure B.12: The simulated contact force in Case 2 at 24 km/h.

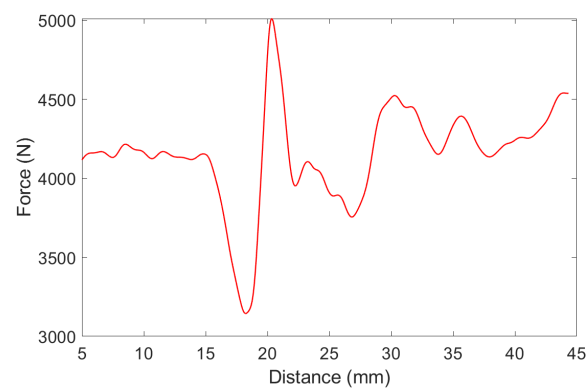


Figure B.13: The simulated contact force in Case 2 at 28 km/h.

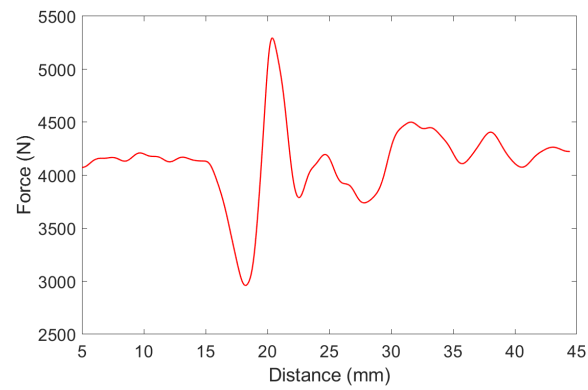


Figure B.14: The simulated contact force in Case 2 at 32 km/h.

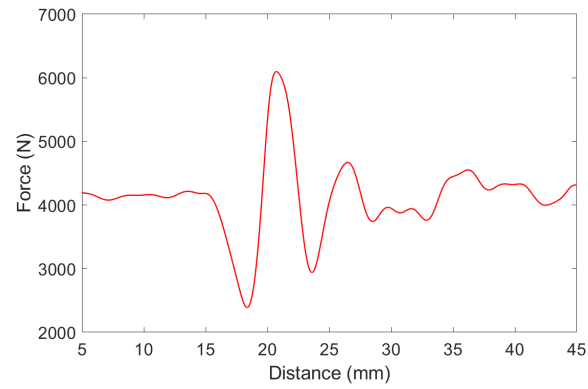


Figure B.15: The simulated contact force in Case 2 at 45 km/h.

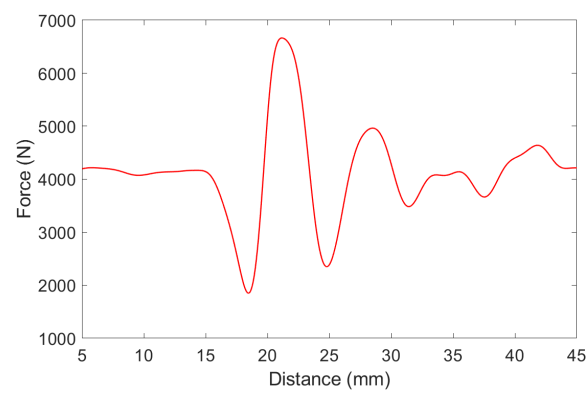


Figure B.16: The simulated contact force in Case 2 at 60 km/h.

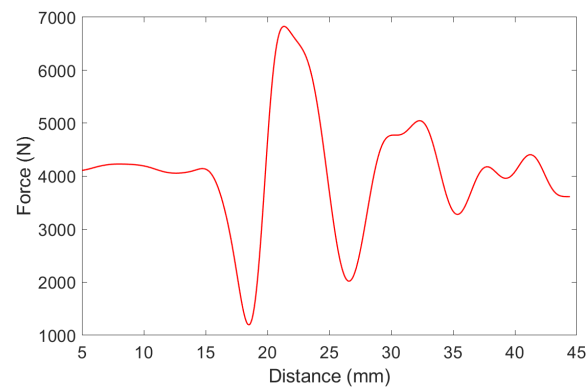


Figure B.17: The simulated contact force in Case 2 at 80 km/h.

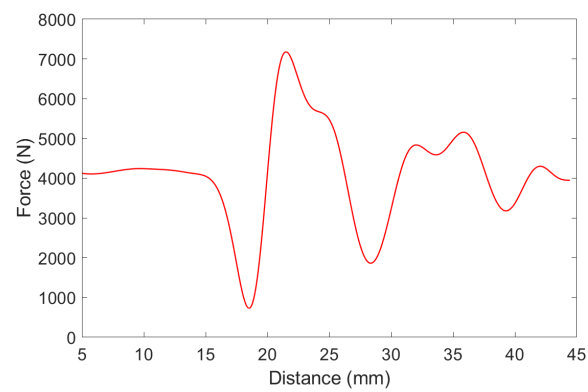


Figure B.18: The simulated contact force in Case 2 at 100 km/h.

C

Simulation - Case 3

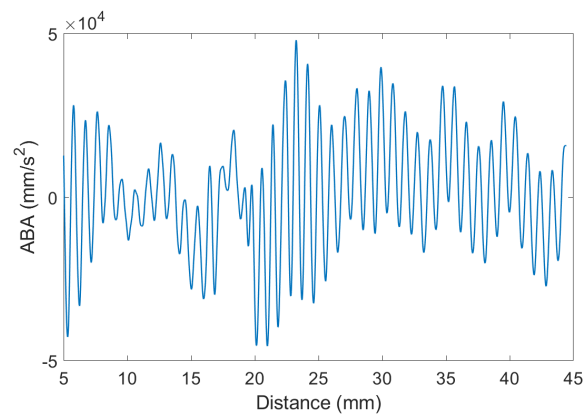


Figure C.1: The simulated ABA in Case 3 at 16 km/h.

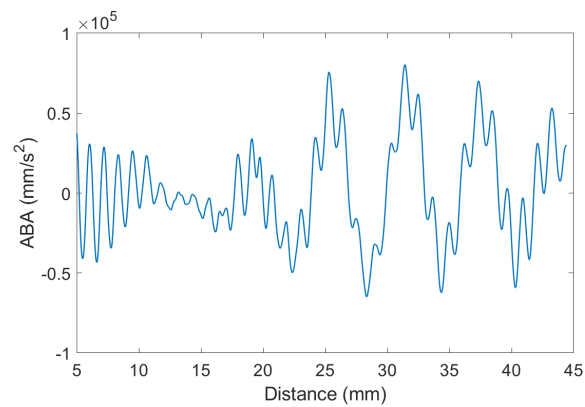


Figure C.2: The simulated ABA in Case 3 at 20 km/h.

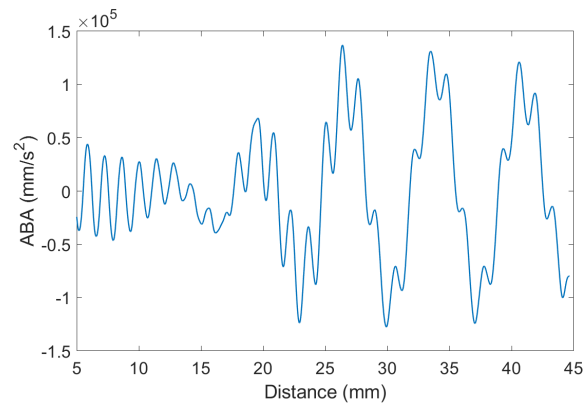


Figure C.3: The simulated ABA in Case 3 at 24 km/h.

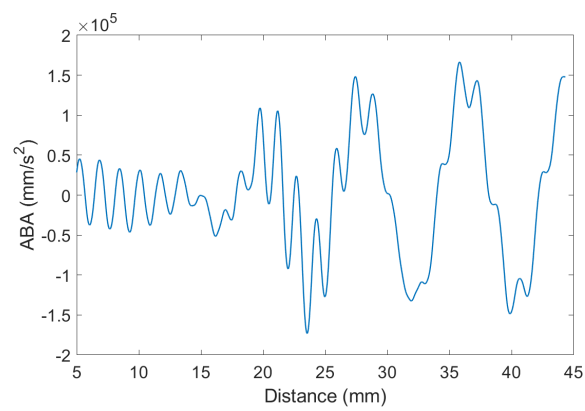


Figure C.4: The simulated ABA in Case 3 at 28 km/h.

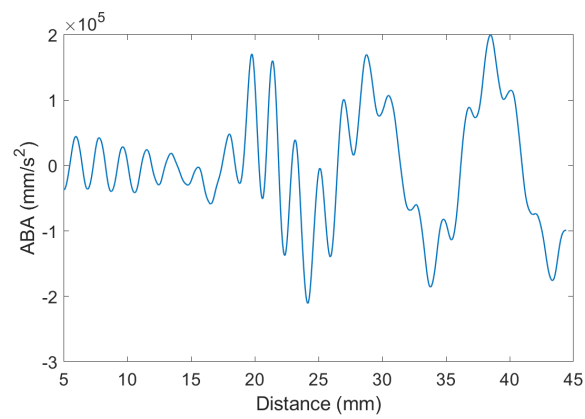


Figure C.5: The simulated ABA in Case 3 at 32 km/h.

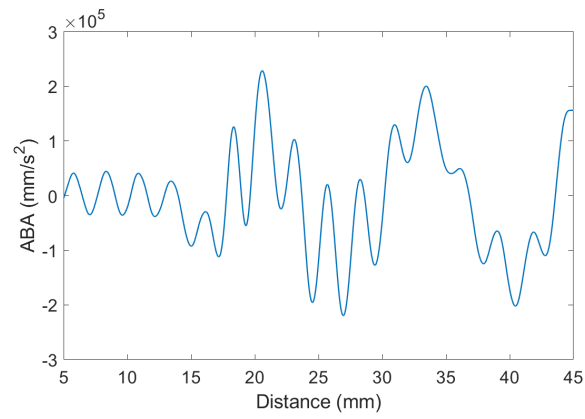


Figure C.6: The simulated ABA in Case 3 at 45 km/h.

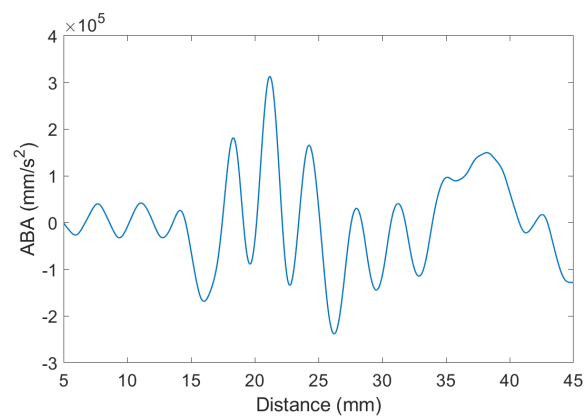


Figure C.7: The simulated ABA in Case 3 at 60 km/h.

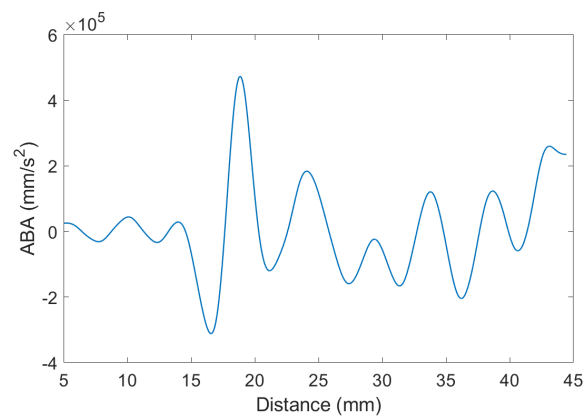


Figure C.8: The simulated ABA in Case 3 at 80 km/h.

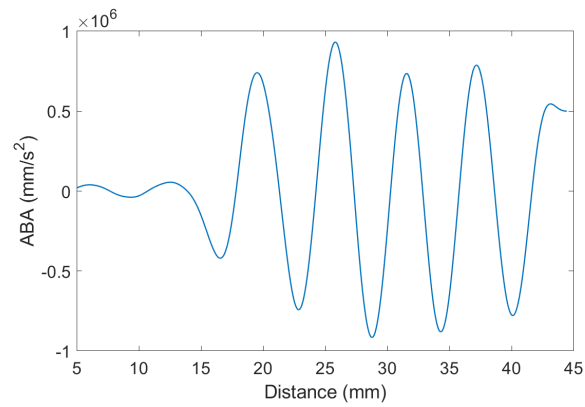


Figure C.9: The simulated ABA in Case 3 at 100 km/h.

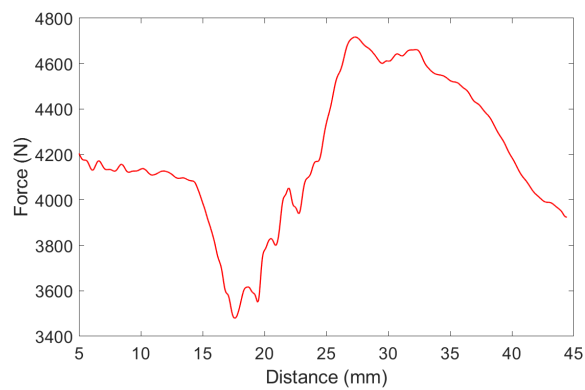


Figure C.10: The simulated contact force in Case 3 at 16 km/h.

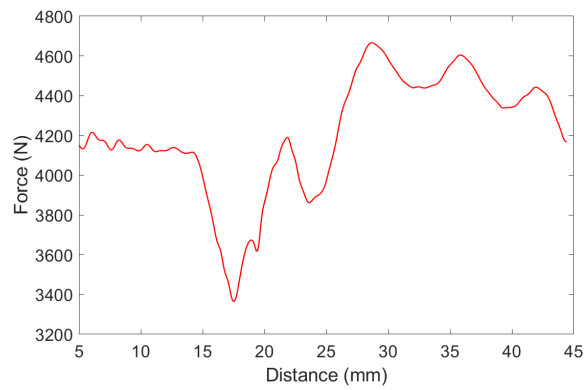


Figure C.11: The simulated contact force in Case 3 at 20 km/h.

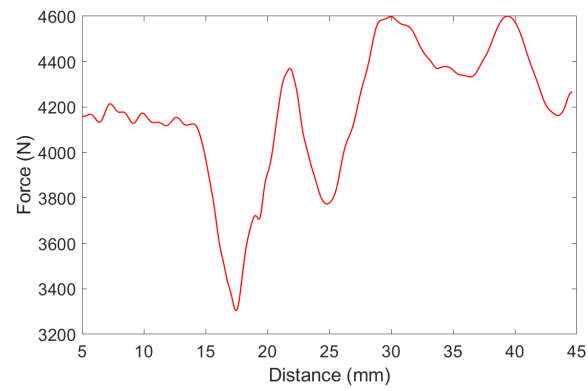


Figure C.12: The simulated contact force in Case 3 at 24 km/h.

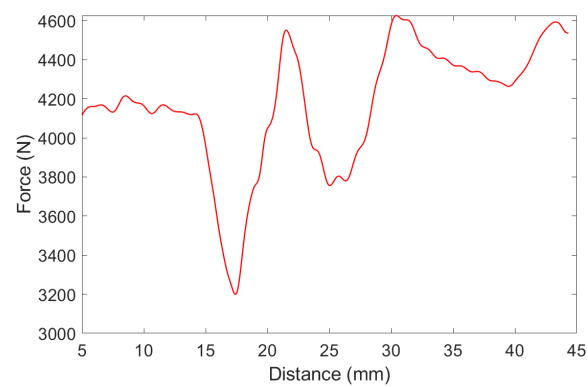


Figure C.13: The simulated contact force in Case 3 at 28 km/h.

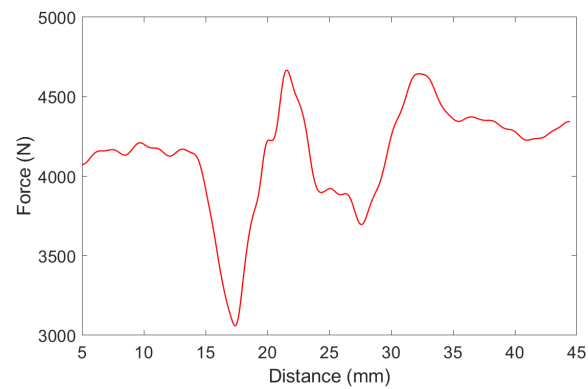


Figure C.14: The simulated contact force in Case 3 at 32 km/h.

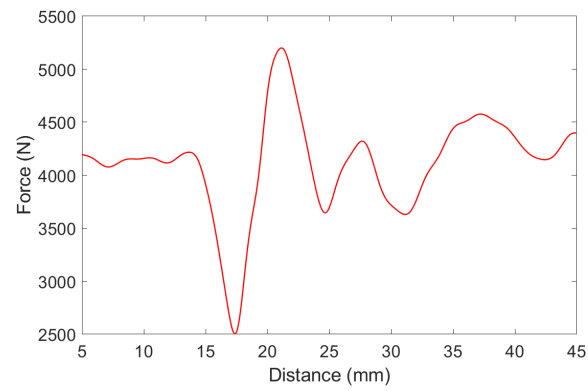


Figure C.15: The simulated contact force in Case 3 at 45 km/h.

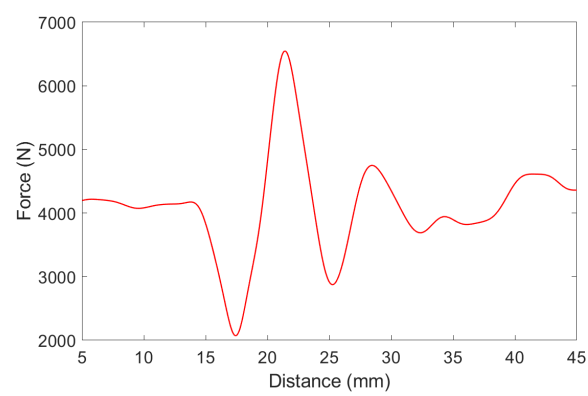


Figure C.16: The simulated contact force in Case 3 at 60 km/h.

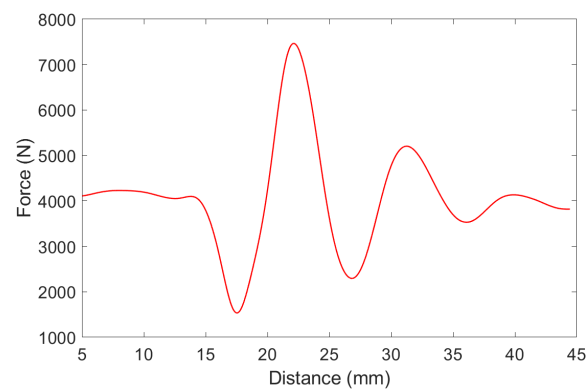


Figure C.17: The simulated contact force in Case 3 at 80 km/h.

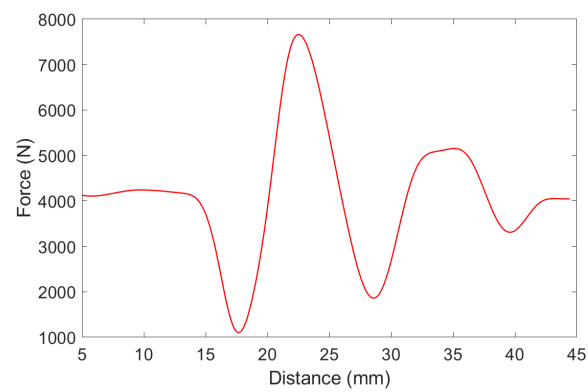


Figure C.18: The simulated contact force in Case 3 at 100 km/h.

D

Simulation - Case 4

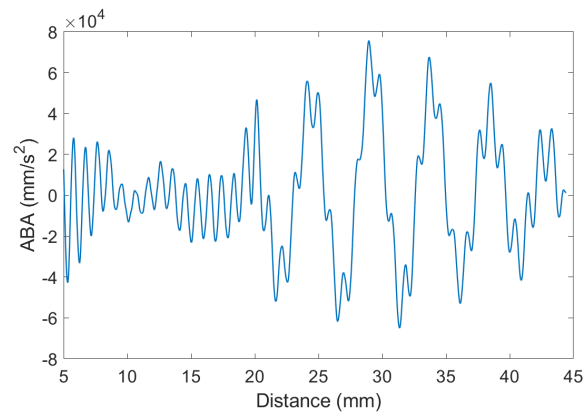


Figure D.1: The simulated ABA in Case 4 at 16 km/h.

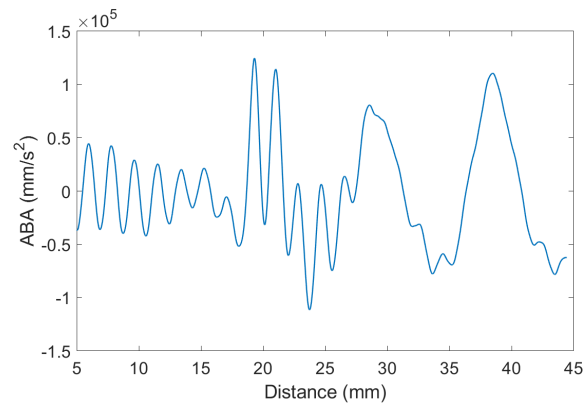


Figure D.2: The simulated ABA in Case 4 at 32 km/h.

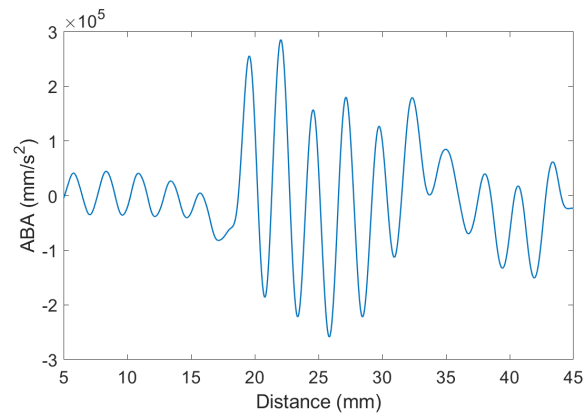


Figure D.3: The simulated ABA in Case 4 at 45 km/h.

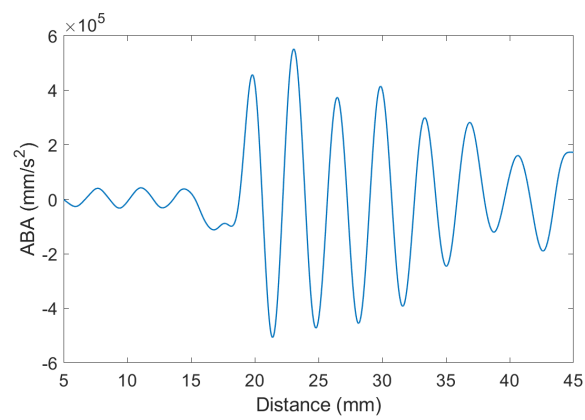


Figure D.4: The simulated ABA in Case 4 at 60 km/h.

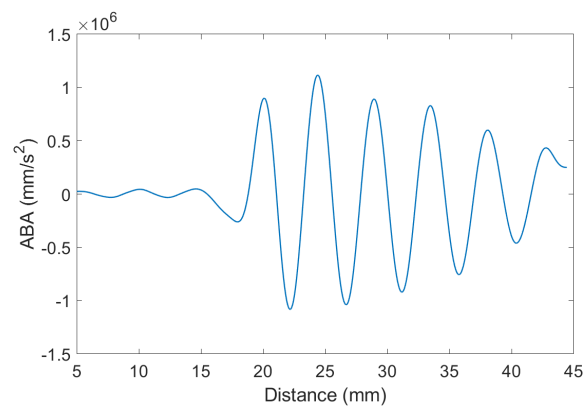


Figure D.5: The simulated ABA in Case 4 at 80 km/h.

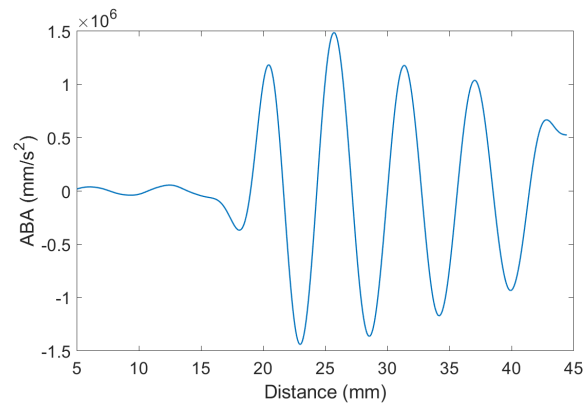


Figure D.6: The simulated ABA in Case 4 at 100 km/h.

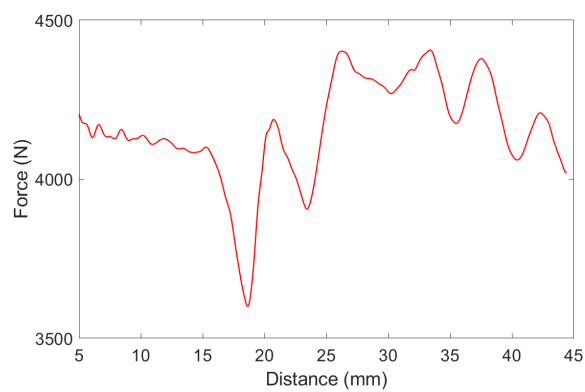


Figure D.7: The simulated contact force in Case 4 at 16 km/h.

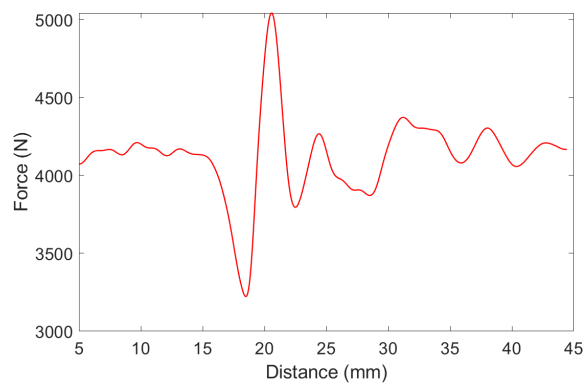


Figure D.8: The simulated contact force in Case 4 at 32 km/h.

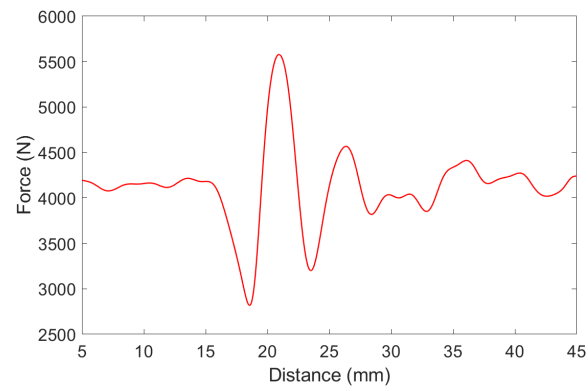


Figure D.9: The simulated contact force in Case 4 at 45 km/h.

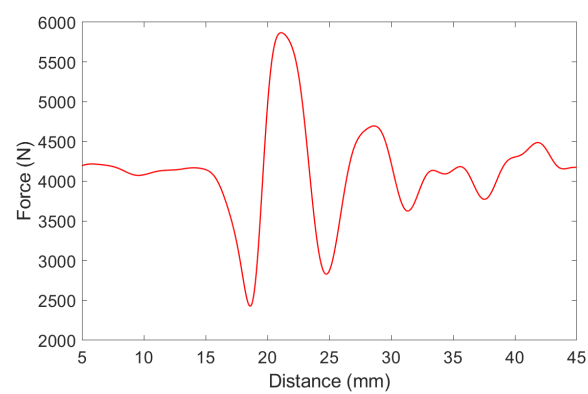


Figure D.10: The simulated contact force in Case 4 at 60 km/h.

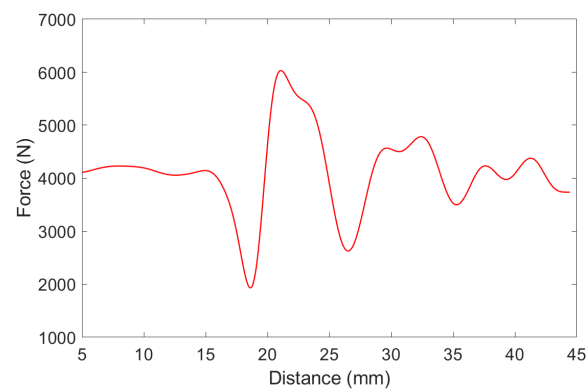


Figure D.11: The simulated contact force in Case 4 at 80 km/h.

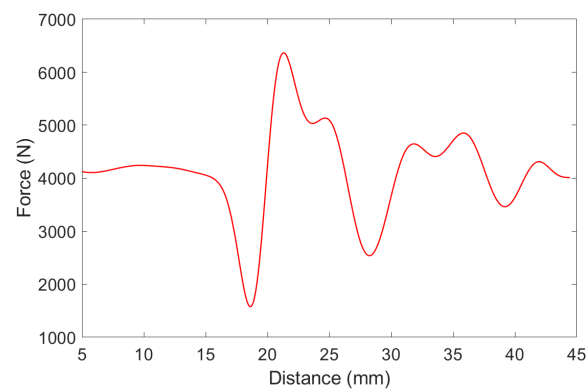


Figure D.12: The simulated contact force in Case 4 at 100 km/h.

E

Simulation - Case 5

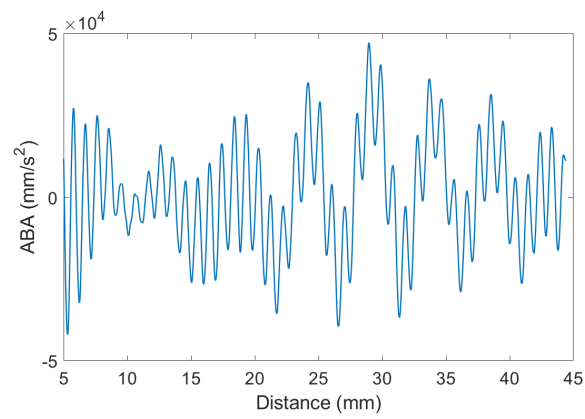


Figure E.1: The simulated ABA in Case 5 at 16 km/h.

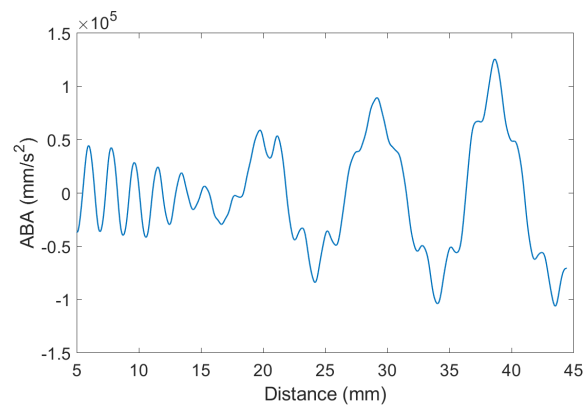


Figure E.2: The simulated ABA in Case 5 at 32 km/h.

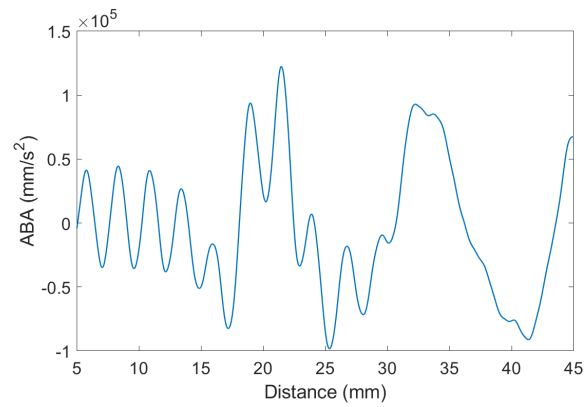


Figure E.3: The simulated ABA in Case 5 at 45 km/h.

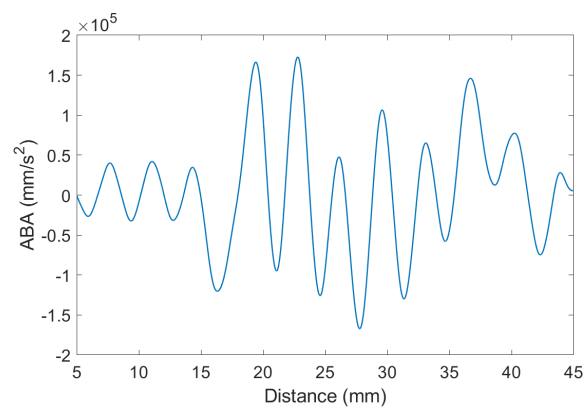


Figure E.4: The simulated ABA in Case 5 at 60 km/h.

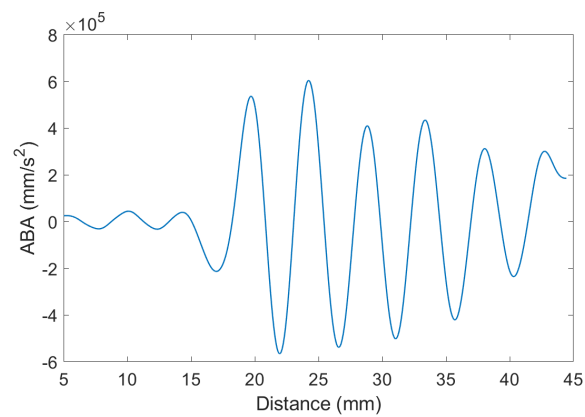


Figure E.5: The simulated ABA in Case 5 at 80 km/h.

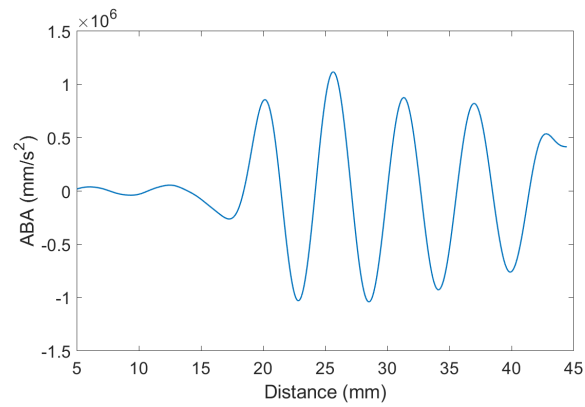


Figure E.6: The simulated ABA in Case 5 at 100 km/h.

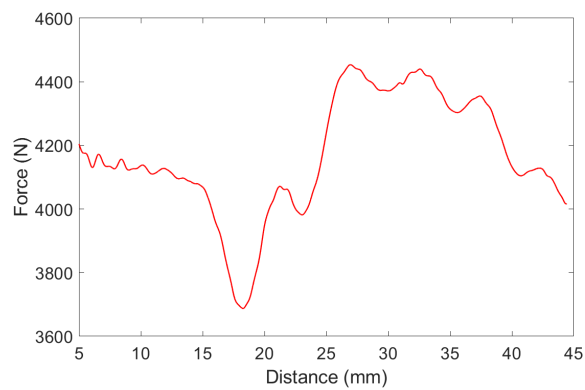


Figure E.7: The simulated contact force in Case 5 at 16 km/h.

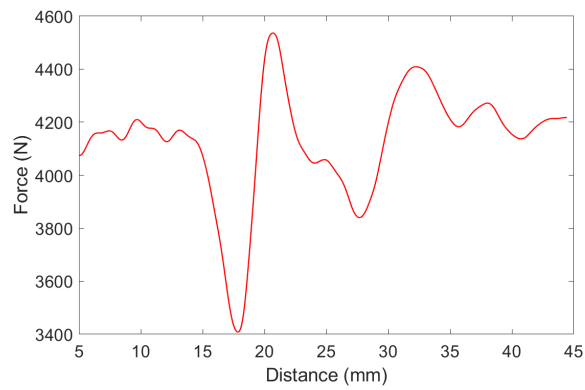


Figure E.8: The simulated contact force in Case 5 at 32 km/h.

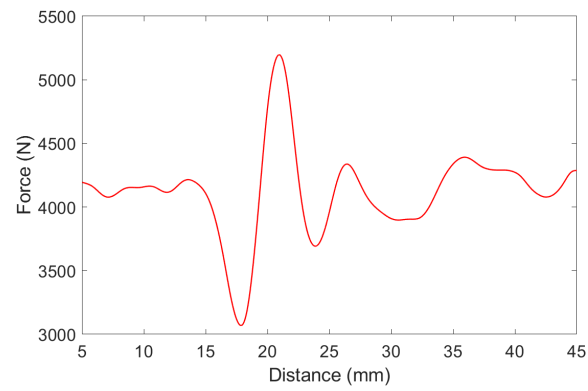


Figure E.9: The simulated contact force in Case 5 at 45 km/h.

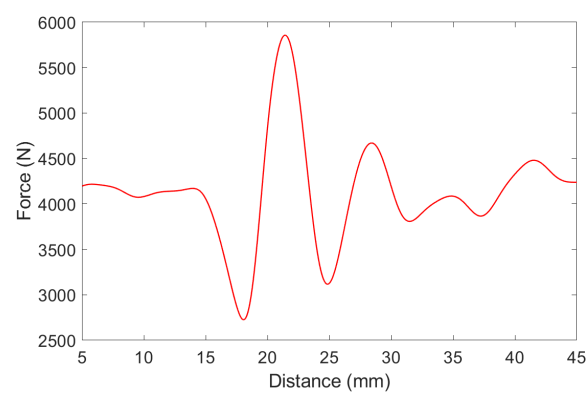


Figure E.10: The simulated contact force in Case 5 at 60 km/h.

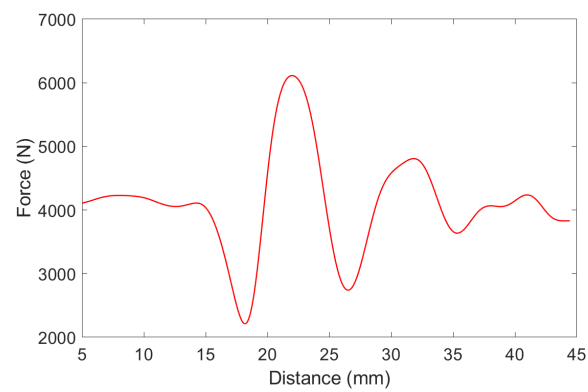


Figure E.11: The simulated contact force in Case 5 at 80 km/h.

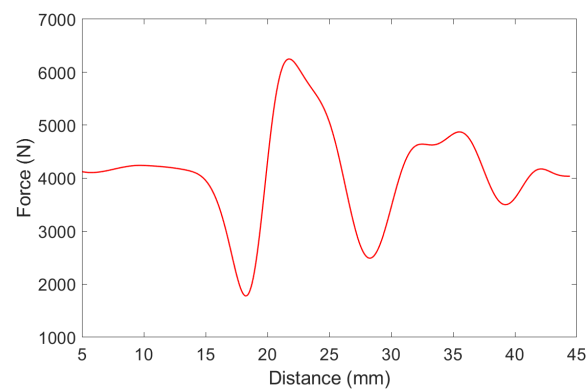


Figure E.12: The simulated contact force in Case 5 at 100 km/h.