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RESEARCH ARTICLE

Research on Estimation Method for Airport Runway Friction Coefficient Based on Numerical Analysis

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ABSTRACT Runway friction coefficient is a crucial parameter that reflects the airworthiness of airport runway and measuring the runway friction coefficient is a prerequisite for ensuring flight safety. Many studies have been conducted on the measurement methods for runway friction coefficient, but most of them are still at the theoretical research level. Although new methods and ideas are constantly being proposed, they are still in the conceptual design and exploration stage. A method based on numerical simulation for runway friction coefficient measurement is proposed in this paper. Firstly, the numerical analysis method is used to explore the interaction mechanism between tire and runway. Based on finite element analysis (FEA), multi-physics field coupling analysis is carried out to reveal the influence of different working conditions on friction coefficient, and to obtain the variation law. Secondly, a friction coefficient measurement method is proposed based on the analysis results, and the friction coefficient estimation models are constructed to achieve a new measurement method that only relies on the tread frictional stress to estimate the friction coefficient with specific working condition. Finally, a friction coefficient measurement system is constructed and used to validate the method. The experimental results indicate that the error between the estimated and actual measurements is from 2.47% to 4.13%. The experiments have verified the effectiveness and accuracy of the estimation model based on numerical analysis method, providing ideas for researching runway friction coefficient measurement methods.

INDEX TERMS Runway friction coefficient, measurement method, numerical simulation, estimation model, verification.

I. INTRODUCTION

With the rapid growth of China's civil aviation industry, guaranteeing the safety of aircraft landings and takeoffs has become a crucial consideration and challenge for airport authorities. The International Civil Aviation Organization (ICAO) has recently conducted a statistical analysis of global flight accidents, revealing that a substantial number of accidents involve aircraft veering or running off the runway during landing deceleration or takeoff acceleration [1]. Accidents bring casualties and property damage, the run-way friction coefficient measurement, therefore, is deemed a critical aspect in ensuring safe takeoffs and landings for aircrafts [2]. In accordance with China's civil airport operation safety management regulations, airports that receive more than 15 aircraft landings per day are obligated to perform tests on runway friction coefficient [3], [4], [5]. Thus, investigating the runway friction coefficient measurement method is significant research and it holds a crucial theoretical and practical significance.

A. RELATED WORKS

In recent decades, extensive research has been conducted by various international organizations, researchers,

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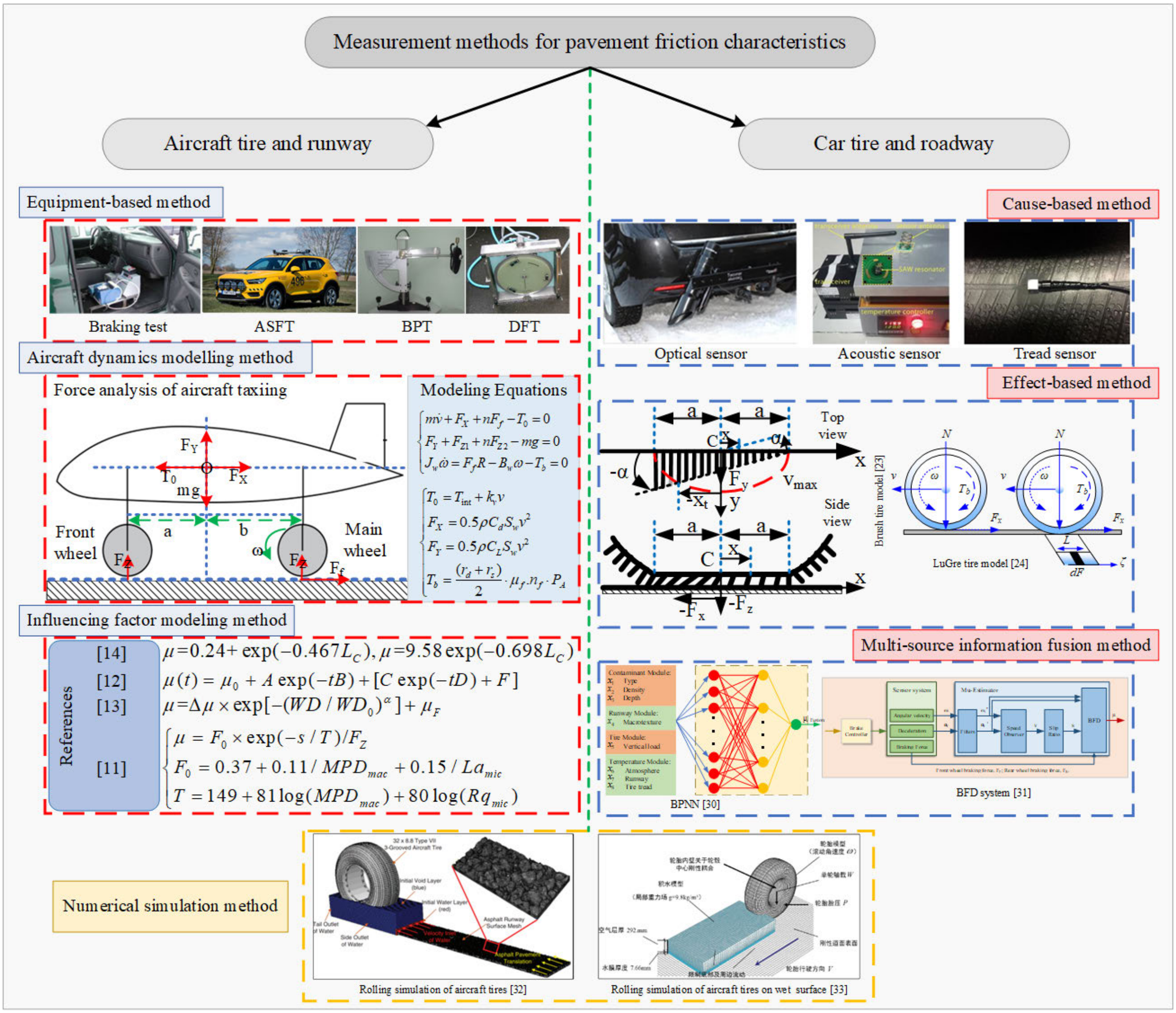

FIGURE 1. **Measurement methods for pavement friction characteristics.**

and aircraft manufacturers, such as Boeing [6] and Airbus [7], on pavement surface friction measurement. This type of surface includes airport runway and roadway, both of which have the same friction mechanism, aircraft tires and airport runway for the former, while automobile tires and roadway for the latter. There are numerous similarities between aircraft and automobile in friction measurement. They learn from each other and develop collaboratively to establish a more comprehensive technology for pavement friction characteristics measurement. These measurement methods and techniques can be described by Figure 1.

The equipment-based method is categorized into two types depending on their outcomes: runway friction coefficient measurement and runway texture characteristics measurement. The detailed measurement methods and equipment involved are given in Ref. [1]. One of the most widely used instruments is the Airport Runway Surface Friction Tester (ASFT), which was developed and reported by our team, see References [3], [4], and [5] for details. Aircraft dynamics modelling is a complex process that combines the equations of motion and equilibrium to decouple the friction coefficient from some relevant parameters in the electro-mechanical actuators of the aircraft braking system [8], [9]. According to the friction mechanism, it is known that the factors affecting friction are mainly related to tire, runway surface, and contaminant. Wahi [10] added environmental factor through literature review and practical investigation, the four major categories were subdivided into 48 sub-items. A large number of influencing factors on tirepavement friction is studied and some mathematical models are obtained. Wang et al. [11] obtained a model that can predict the friction coefficient at any vehicle speed only from the macrotexture and microtexture; Cui et al. [12] obtained a model that can predict the friction coefficient by the degree

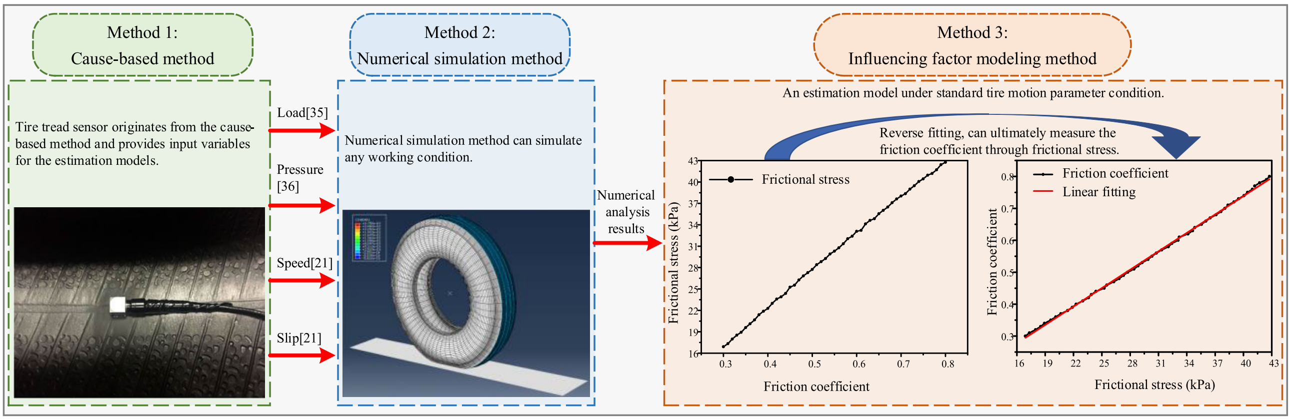

FIGURE 2. **Research on friction coefficient measurement method based on a combination of multiple methods.**

of asphalt pavement surface polishing; Do et al. [13] obtained a model that described the relationship between water film thickness and friction coefficient; Luca et al. [14] obtained an empirical friction decay model; Wahi obtained a model to convert 10 independent variables into 7 π-terms [10].

The cause-based method employs sensors to measure parameters associated with friction and then establishes correlations between these parameters and friction coefficient. Andersson et al. [15] suggested that sensor measurements can range from wheel sound to the optical properties of the road surface. These sensors include acoustic sensors [16], [17], [18], optical sensors [19], [20], tread sensors [21], [22], and composite sensors. The effect-based method involves developing a model for a specific component or system, and then solving friction coefficient. Tire models, which describe the relationship between mechanical characteristics and motion, are commonly used for modeling [23], [24]. A concept of 'smart tire' has been proposed, whereby tires could serve as a specialized type of sensor to measure friction or related parameters, noteworthy studies in References [25], [26], and [27]. The multi-source information fusion method is derived from the cause-based method, which means that more than 2 parameters are fused by different fusion algorithms. These fusion algorithms include Kalman filtering [28], frequency domain data fusion [29], neural networks [30], and others [31].

In recent years, numerical simulation has gradually become an important research method, it combines the concept of finite element with numerical calculation to achieve the purpose of researching various problems. It can be used to realize the numerical analysis of friction characteristics with different working conditions, whether it is aircraft-runway [32], [33] or automobile-roadway [34].

B. PROBLEM STATEMENT

Although runway friction coefficient measurement techniques have been significantly developed, there are few methods that can be used for practical measurements and much of the research works remain at a theoretical level. Numerous novel methods and concepts have been suggested, yet they remain in the phase of conceptual development and exploration with limited systematic evaluation and summary of post-implementation and validation experiences. To address the problem, our team has been trying to present new ways. From the above-mentioned related works, it can be seen that there are roughly seven measurement methods, and the combination of different methods to realize the friction coefficient measurement can be considered as a new attempt.

The friction coefficient between tire and runway is influenced by many factors, so the modeling method based on influencing factor is able to reflect the friction coefficient intuitively through the relevant parameters. The several mathematical models listed in Figure 1 involve many parameters, which poses difficulties for practical applications. According to the cause-based method, tire tread sensors can monitor tire load, inflation pressure, speed, and slip rate, providing convenience for selecting influencing factors. It is challenging to monitor multiple variables simultaneously due to the high-speed movement of the tires, numerical analysis method, therefore, can simulate tire-pavement interactions with any working condition. In this study, we combined the cause-based method (tread sensor), influencing factor modeling method, and numerical simulation method. Figure 2 illustrates the connection among these methods [21], [35], [36].

C. OBJECTIVES OF RESEARCH

ICAO, European Union Aviation Safety Agency, and Civil Aviation Administration of China (CAAC) have proposed the development of new methods to measure runway friction coefficient. Firstly, this paper proposes to use numerical analysis to simulate the interaction between tire and runway, and to carry out multi-physics field coupling analysis based on finite element; secondly, to construct models that can realize the estimation of runway friction coefficient; and lastly, to construct a runway friction coefficient measurement system for validating its correctness and effectiveness. In view of these problems, the following objectives are to be achieved:

1) Exploring the interaction mechanism between tire and runway, revealing the influence of tire inflation pressure, load, speed, and slip on friction coefficient;
2) Proposing friction coefficient measurement method based on the analysis results, and constructing estimation models;
3) Constructing friction coefficient measurement system and verifying the accuracy and validity of the given estimation model.

D. SUMMARY OF CONTRIBUTIONS

Despite significant developments in the measurement technology of airport runway friction coefficient since its importance was recognized, there were still few practical methods available. As a result, measuring runway friction coefficient remains a significant challenge in practice. In this paper, we proposed a finite element-based method for measuring the friction coefficient, realized the analysis of the influencing factors and the establishment of the estimation models, and carried out experimental to verify the proposed method. To investigate the influence of different tire motion parameters on the friction coefficient, a finite element simulation method was used to numerically simulate the relationship between tire tread frictional stress and friction coefficient wirh different motion parameters, including inflation pressure, load, speed, and slip rate. Secondly, the fitting method was used to solve for the friction coefficient in reverse, obtaining the relationship between friction coefficient and frictional stress. Estimation models were then established for different working conditions, resulting in a measurement method that relied solely on the frictional stress to estimate friction coefficient with specific working condition. Finally, a measurement system was constructed for actual measurement, and the validation of the estimation model was carried out.

This paper firstly presents research background, related workings, and research objectives. The remaining sections of this paper are as follows: Section II is theory of rubber sliding, which provides a theoretical basis for finite element method; Section III is modeling process of tire-runway multifield coupling; Section IV is multifield coupling analysis that presenting the influence of univariate and multivariable on the friction coefficient; Section V not only established estimation models, but also constructed a measurement system to complete the verification work. Section VI is conclusion and points out feasible research directions for future.

II. THEORETICAL BASIS OF TIRE-RUNWAY MULTIFIELD COUPLING ANALYSIS

Most of the runway friction coefficient measurements utilize tires with slip. For both automobile and aircraft, the sole material in contact with pavement surface is tread rubber. Rubber exhibits distinct friction properties compared to most solids owing to its low modulus of elasticity and high internal friction over a wide frequency region. According to Persson [37], friction coefficient is influenced by the roughness of runway surface and sliding speed. When rubber glides over the runway surface, the surface's roughness generates vibratory forces that lead to energy dissipated. This energy dissipation is related to rubber sliding speed (v), contact area (A_s), and frictional shear stress (σ_f). Equation (1) demonstrates the resulting energy dissipation at the moment t_0.

$$\Delta E = \sigma_f \cdot A_S \cdot v \cdot t_0 = u\sigma \int d^2x \cdot dt$$
$$= (2\pi)^3 \int d^2q \cdot d\omega \cdot (-i\omega) u(\mathbf{q}, \omega)\sigma(-\mathbf{q}, -\omega) \quad (1)$$

where, u is rubber surface deformation function, σ is rubber surface stress distribution function, q is wave vector, $\boldsymbol{q} = (q_x, q_y)$, and ω is rubber surface's vibration frequency. The surface power spectral density function $C(q)$ is introduced, and using the polar coordinate expression, frictional shear stress can be expressed by (2).

$$\sigma_f = \frac{1}{2} \int d^2q \cdot q^2 \cos\theta \cdot C(q) \cdot \mathrm{Im}\left[\frac{E(qv\cos\theta)}{1-\upsilon^2}\right] \quad (2)$$

where, E is rubber modulus function, Im[-] denotes the imaginary part taken as [-], and υ is Poisson's ratio. Thus, friction coefficient can be defined as the ratio of frictional shear stress to vertical stress (σ_v), i.e.:

$$\mu = \frac{\sigma_f}{\sigma_v} = \frac{1}{2} \int d^2q \cdot q^2 \cos\theta C(q)P(q)\mathrm{Im}\left[\frac{E(qv\cos\theta)}{(1-\upsilon^2)\sigma_v}\right]$$
$$= \frac{1}{2} \int d^2q \cdot q^3 C(q)P(q) \times \int_0^{2\pi} d\theta$$
$$\cdot \cos\theta \mathrm{Im}\left[\frac{E(qv\cos\theta)}{(1-\upsilon^2)\sigma_v}\right] \quad (3)$$

Rubber sliding entails energy storage and dissipation, both of which are described by the complex modulus. The process is simplified into a three-element model that describes the connection between stress and strain. This model requires many parameters, including those related to rubber material and runway surface. The study employs finite element method for numerical analysis and calculation, enabling a mechanical analysis of the interaction between rubber and runway surface through the use of finite element calculation software.

III. MODELING OF TIRE-RUNWAY MULTIFIELD COUPLING ANALYSIS

A. FINITE ELEMENT ANALYSIS PROCESS

Friction coefficient can be determined by the ratio of tread frictional stress to vertical stress, as shown in (3). This provides a theoretical foundation for investigating the correlation between tread frictional stress and friction coefficient with different working conditions using numerical analysis. Tire FEA is a highly intricate computational problem in engineering that involves various factors, including geometry, nonlinear materials, and contact. The analysis process comprises three stages: pre-processing, solution process and post-processing. To complete each stage, specific software programs such as CAD, Hypermesh and ABAQUS are employed. Figure 3 illustrates the process of FEA utilized in this paper.

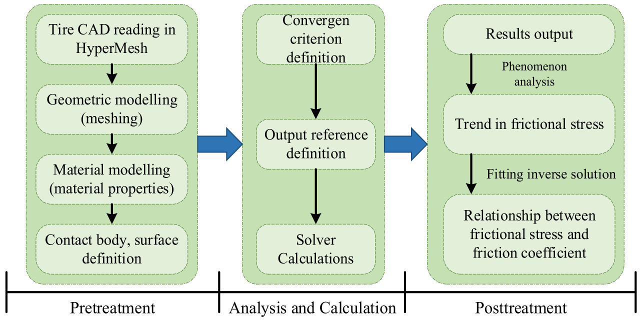

FIGURE 3. FEA process utilized in this paper.

B. COMPOSITION AND GRID DIVISION OF RUBBER MATERIAL

A tire is comprised of several components: tread, bead, belt ply, inner liner and sidewall. The tread is the part that makes direct contact with the runway surface and is made up of crown and shoulder. The bead refers to the part in contact with wheel hub and consists of triangular rubber, steel wire rim and bead rubber. The belt ply is a kind of composite material, comprising of steel wires and nylon filaments, that is sandwiched between crown and carcass. We selected the measuring wheel of the ASFT depicted in Figure 4, and the relevant parameters are given in Table 1.

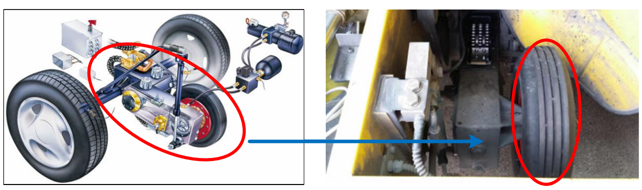

FIGURE 4. Measuring wheel located on the ASFT rear axle.

TABLE 1. Measuring wheel parameters for ASFT.

Designation	Parametric	Unit
Size	4.00-8	/
Radius	254±38	mm
Outer diameter	417±5	mm
Inflation pressure	210	kPa
Tread width	61±2.5	mm
Cross-section width	104±3.8	mm

The relevant parameters are determined based on Table 1, a siped, light-patterned tire, with a tread width of 60 mm, a cross-section width of 105 mm, and a tread height of 102.5 mm is chosen. Although the tire's main components are rubber products, they have different material properties. Hence, in numerical analysis process, it is necessary to couple these materials with different properties in order to analyze tire-runway's performance. Various sources have simplified tire model into different numbers of components: References [38] and [39] into seven, References [40] and [41] into eight, and Ref. [42] into nine. Eight tire components were selected for numerical analysis in this paper, they were sidewall, tread, shoulder, carcass, inner liner, belt ply, triangle rubber, and wire rim. These components have been meshed, and the meshing results are presented in Figure 5(a). The two-dimensional cross-section after grid division can generate a three-dimensional tire finite element model through rotation instruction, as shown in Figure 5 (b).

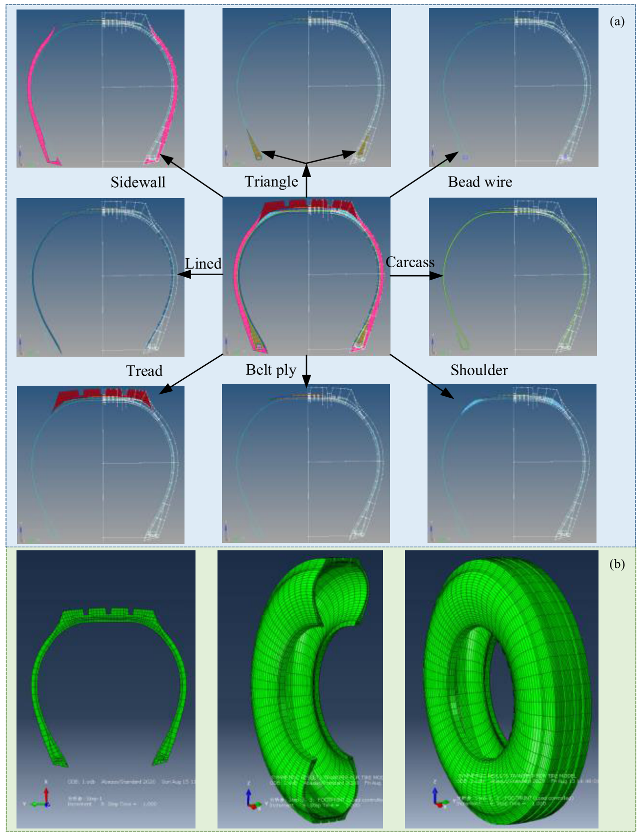

FIGURE 5. Tire finite element modeling process: (a) cross-section mesh division; (b) a 3D model by rotating the cross-section.

C. RUBBER MATERIAL PARAMETERS

After determining tire's rubber composition, it's essential to conduct tensile tests on the various parts of the rubber material and subsequently establish the intrinsic model for each part. Rubber material can be considered as a kind of incompressible hyperelastic material, whereby its stress-strain relationship portrays a nonlinear relationship when tensile experiments are performed. Three commonly used nonlinear models are applied to FEA of rubber elastomers, including Moony-Rivlin model, Neo-Hookean model, and Yeoh model, as described in previous studies [40], [41]. We select Neo-Hookean model, which is a simplified variation of the Moony-Rivlin model, to develop the intrinsic model for each component. The mathematical expression of this model is presented in (4).

$$U = C_{10}(I_1 - 3)^2 + \frac{1}{D_1}(J_{el} - 1)^2 \quad (4)$$

where, C_{10} and D_1 are material coefficients, and J_{el} is the volume ratio before and after compression. This model has only two parameters and is suitable for small rubber deformation. The material parameters can be found in Ref. [43], while Table 2 provides information for the coefficients of each component.

TABLE 2. Coefficients of various components for Neo-hookean model [43].

Part	Parametric	
	C_{10}	D_1
Tread	0.671	0.03
Carcass	0.839	0.024
Sidewall	0.336	0.06
Shoulder	1.006	0.02
Lined	0.503	0.024
Triangle	0.671	0.03
Banding	0.839	0.024

The belt ply, with steel wire and cord forming the frame structure serves as tire's backbone material, which is then overlaid with rubber on the surface. The skeleton material is a kind of composite material, its properties can be defined in ABAQUS by reinforcement (*Rebar) and the cord is embedded into the rubber material by *Embedded Element command. In this paper, the parameters of the skeleton material for FEA are given in Table 3.

TABLE 3. Tire frame material parameters.

	Cap ply	Belt ply1	Belt ply2	Carc -ass	Bead wire
Density (kg·m-3)	1240	10500	10500	1400	22400
Poisson's ratio	0.32	0.28	0.28	0.28	0.28
Young's modulus (MPa)	6554	114907	114907	4200	203660
Cord spacing (mm)	0.9	1.43	1.43	1.37	0
Cord cross-sectional area (mm2)	0.24	0.23	0.23	0.20	0.64

D. SETTING MODEL BOUNDARY CONDITIONS

For multi-field coupling analysis of tire and road system using ABAQUS, an implicit solver is necessary. This paper divides the analysis into two processes: tire modeling and tire loading, which include four analysis steps. The boundary conditions for each step are provided below.

1) 2D modeling, constraining the wheel hub reference point with 6 degrees of freedom, applying a small displacement of 0.2mm to the tire to bind and constrain it to the wheel hub;
2) Tire inflating, applying Y-direction displacement to both wheel hubs until they are in contact. Then, applying a uniformly distributed load to tire inflation surface to simulate inflation pressure;
3) 3D modeling, importing road surface model, applying a negative X-direction displacement of 2mm to the road surface model, ensuring that the tire is in initial contact with the road surface, and applying a negative X-direction load to the road surface after contact balance;
4) Steady state rolling transport analysis, applying negative Z-direction translational velocity to the road surface and rotational velocity to the tire.

The analysis steps outlined above involve several boundary conditions, including inflation pressure, load, velocity, and slip rate. In our research, we utilised an INP file format to facilitate the setting and modification of these conditions.

IV. TIRE-RUNWAY MULTIFIELD COUPLING ANALYSIS

A. STEADY-STATE TRANSPORT ANALYSIS

The tread rubber's friction properties are investigated using steady-state rolling analysis in ABAQUS FEA. It is also known as steady-state transport analysis, which combines Lagrangian and Eulerian methods. One benefit of this method is that the mesh remains stationary during the analysis, while the material moves within it. The conventional Lagrangian method can replicate rolling, but the process is time-intensive and demands refinement for all meshes on the tread. In contrast, the hybrid method necessitates refinement solely for the contact surfaces and achieves precision results. Based on the ASFT, the wheel's motion state can be analyzed as kinematic problem of a tire rolling linearly using ABAQUS. Equation (3) shows that frictional stress has closest relation with friction coefficient and is highly dependent on tire load, inflation pressure, speed, and slip rate. In this section, we investigate and analyze the relationship between friction coefficient and frictional stress applied to the tread in distinct parameter conditions using numerical analysis. The range of tire parameters for numerical analysis is displayed in Table 4.

TABLE 4. Parameters range of tire parameters.

Symbol	Parametric	Range	Unit
F_z	Load	80~120，increment 10	kgf
p	Inflation pressure	190~230，increment 10	kPa
v	Speed	60~100，increment 10	km/h
s	Slip rate	0.13~0.17, increment 0.1	/
μ	Friction coefficient	0.3~0.8，increment 0.01	/

To perform numerical analysis, the friction coefficient of the contact surfaces (tire and runway surface) needs to be given, and then the tread frictional stress can be obtained through calculation. Any changes in friction coefficient will inevitably alter the tread frictional stress, Therefore, alterations in the friction coefficient with various working conditions can be determined through the tread frictional stress distribution. To determine standard motion parameters, we adopt $F_z = 100$kgf, $p = 210$kPa, $v = 90$km/h, and $s = 0.15$ (these parameters are also utilized in practical measurement on ASFT). With the standard condition, the tread

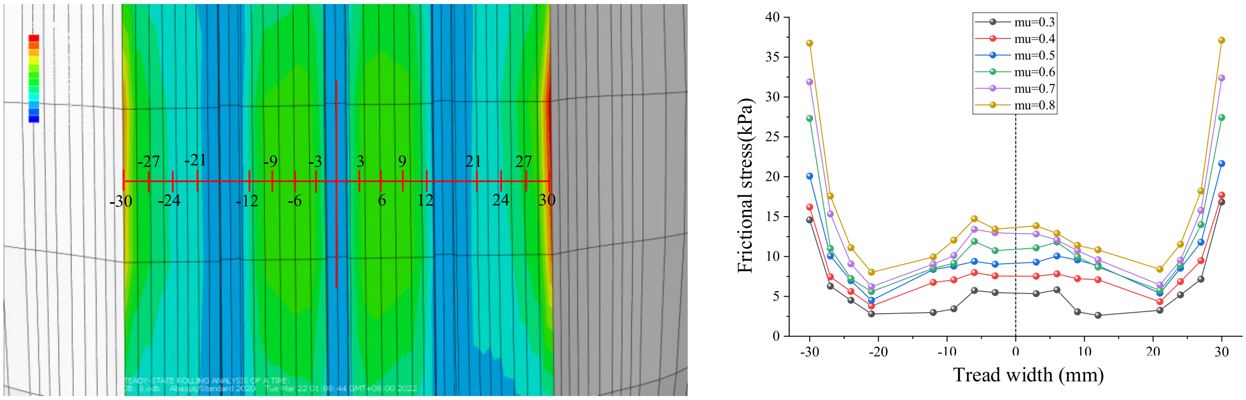

FIGURE 6. **Tread frictional stress distribution map.**

frictional stress distribution corresponding to different friction coefficients is shown in Figure 6.

B. UNIVARIATE WORKING CONDITION

As depicted in Figure 6, the frictional stresses in the ABAQUS field output are not averaged across the entire contact area, but rather indicate the stress level applied to different areas based on color. Ref. [44] defines the limiting reference stress, which captures all working conditions, as the highest stress level of the subdomain. We employ the identical method, specifically, all frictional stresses derived from numerical analysis are considered as the limiting frictional stresses. Results from FEA calculations show the relationship between friction coefficient and frictional stress with varying load, pressure, speed and slip conditions, as shown in Figure 7. When conducting univariate condition analysis, only one variable is altered while the other three are kept as standard parameters.

To further analyze the changes with different working conditions observed in Figure 7, we combine (3) with the appropriate analysis, except for the slip conditions. Ref. [30] states that when a tire is braked, it exhibits both rolling and sliding. As the slip rate increases, the friction coefficient initially increases before decreasing.

1) Analysis of Figure 7(a) demonstrates the following trend: with identical load condition, the vertical stress remains unchanged, while the tread frictional stress increases as the friction coefficient increases; with identical friction coefficient condition, the vertical stress increases with load, while the tread frictional stress also increases when keeping the friction coefficient constant.
2) Analysis of Figure 7(b) demonstrates the following trend: with the same inflation pressure, vertical stress remains constant as the load does not alter. An increase in friction coefficient leads to an elevation in tread frictional stress; with identical friction coefficient condition, when inflation pressure increases, the area of contact between the tire and the runway surface reduces, while the load on the tire remains unaltered. This subsequently results in an increase in vertical stress. If the friction coefficient remains constant, the frictional stress will also increase.
3) Analysis of Figure 7(c) demonstrates the following trend: with identical speed condition, the vertical stress remains unchanged as the load does not alter. With an increase in the friction coefficient, the tread frictional stress will also increase; with identical friction coefficient condition, the vertical stress decreases as speed increases, if the friction coefficient remains constant, the frictional stress is also reduced.

C. MULTIVARIATE WORKING CONDITION

The interaction between tire and runway is subject to various factors, hence it is necessary to analyze the frictional stress trend with multivariate working conditions. The working conditions consist of two variable combinations including inflation pressure-load, load-velocity, and velocity-slip coupling, and three variable combinations including inflation pressure-load-velocity and load-velocity-slip coupling. The three-dimensional frictional stress distribution, generated via the interpolation method, were plotted for two variable conditions with different friction coefficients. The coupling of inflation pressure and load is depicted in Figure 8(a) ($\mu = 0.3, 0.5, 0.7$), the coupling of load and speed is depicted in Figure 8(b) ($\mu = 0.4, 0.6, 0.8$), while the coupling of speed and slip is depicted in Figure 8(c) ($\mu = 0.3, 0.8$).

The frictional stress distribution with the coupling of three variables is conveyed using a four-dimensional graph, and the color scale represents the fourth dimension's magnitude. Figure 9(a) displays the four-dimensional scatter plots of frictional stresses caused by inflation pressure-load-velocity coupling with different friction coefficients ($\mu = 0.3, 0.5, 0.7$), while Figure 9(b) presents the plots for load-velocity-slip coupling ($\mu = 0.4, 0.6, 0.8$).

Figure 7 shows the frictional stress trend for a single variable, whereas Figures 8 and 9 illustrate frictional stress trend resulting from the coupling of two or three variables.

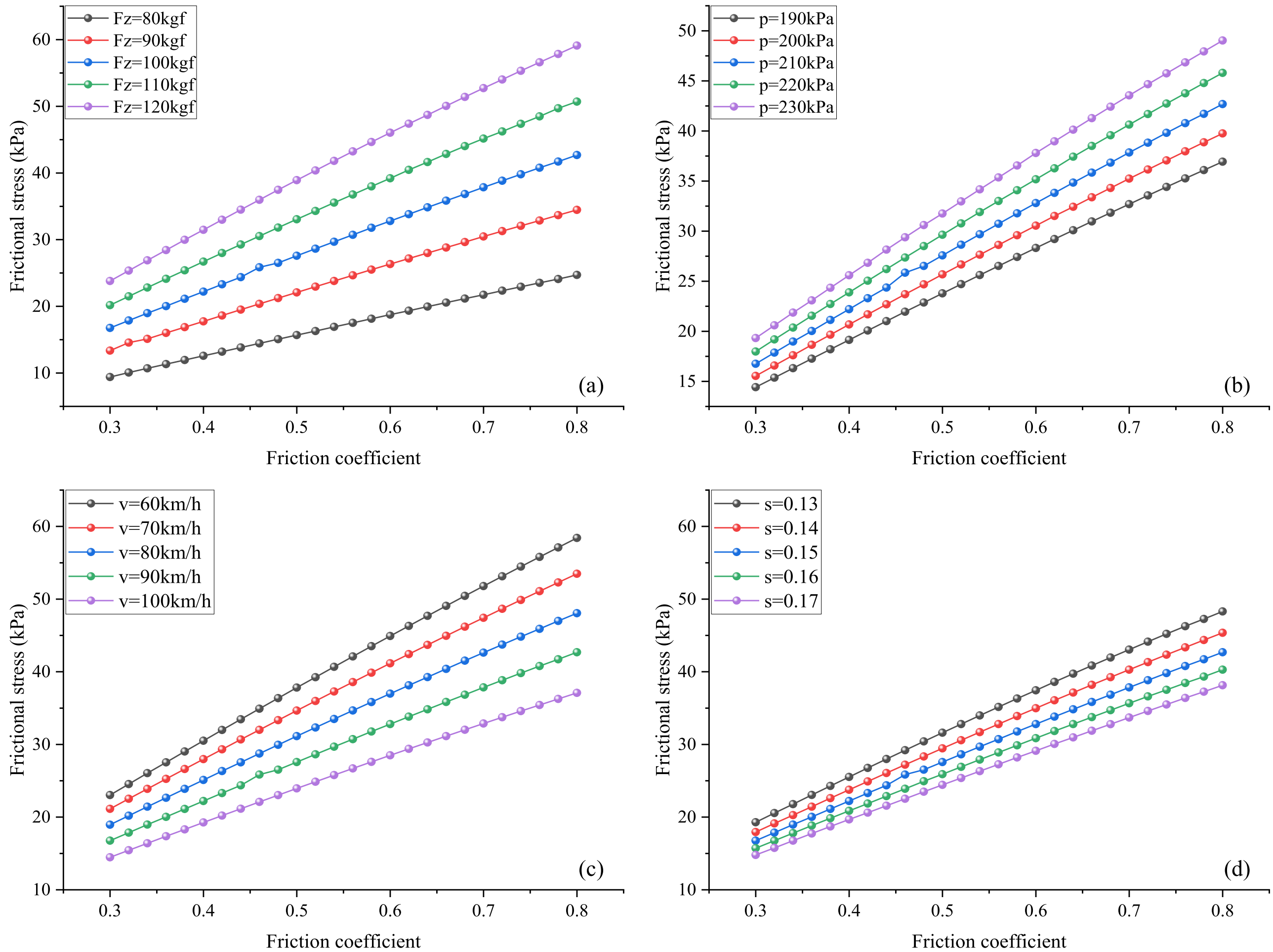

FIGURE 7. Relationship between friction coefficient and frictional stress with different conditions: (a) load conditions; (b) inflation pressure conditions; (c) speed conditions; (d) slip rate conditions.

The trend of multivariate coupling can be combined with that of individual variables for analysis to provide insight into their relationship. It can be concluded that the frictional stress increases with an increase in load and inflation pressure, as well as a decrease in velocity and slip rate, regardless of the coupling of any variable.

V. ESTIMATION MODELS CONSTRUCTION AND VALIDATION

A. ESTIMATION MODELS CONSTRUCTION

The previous section examined the relationship between tread frictional stress and friction coefficient with various univariate and multivariate conditions. In these analyses, friction coefficient functioned as independent variable and frictional stress as dependent variable. To achieve friction coefficient as a target for measurement, we proposed a solution to determine it through a fitting inverse. This method used frictional stress as independent variable and friction coefficient as dependent variable. Notably, the mapping function changed from $f(F_z, p, v, s, \mu) \rightarrow \sigma_f$ to $f(F_z, p, v, s, \sigma_f) \rightarrow \mu$.

As a result, this method proved that it is feasible to estimate runway friction coefficient purely through assessing tread frictional stress in a set working condition. Figure 10 (a) reveals the relationship between frictional stress and friction coefficient in standard working condition, whereas Figure 10(b) reveals the relationship between friction coefficient and frictional stress through fitting. Furthermore to the standard working condition, other working conditions listed in Table 4 were fitted separately and the fitting outcomes can be observed in Figure 11.

According to Figure 10 and Figure 11, it can be seen that 17 working conditions were selected for linear fitting. The fitting form is $y = a + b \times x$, where, x is frictional stress, y is friction coefficient. The linear fitting equations for each working condition are shown in Table 5.

B. EXPERIMENTAL PLATFORM CONSTRUCTION

The above analysis suggests that the estimation models are founded on numerical analysis without any subsequent systematic evaluation post-validation. Our team has previously reported on ASFT's measurement principle and has

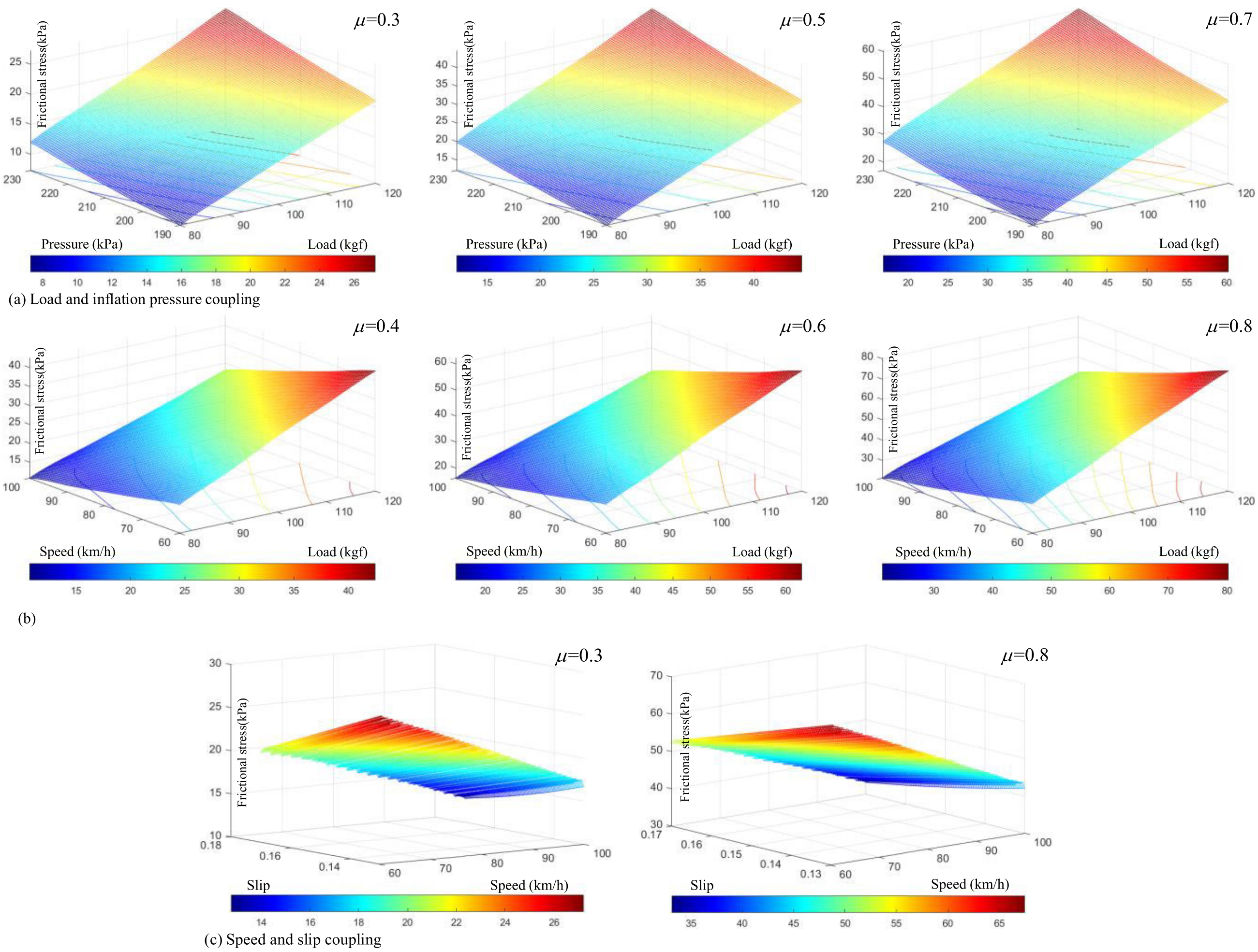

FIGURE 8. Frictional stress distribution with different working conditions (Coupling of two variables).

TABLE 5. Fitting results for different working conditions.

Working Conditions		Intercept, a	Slope, b	Adjusted R^2
Standard (100kgf, 210kPa, 100km/h, 0.15)		-0.02996	0.01921	0.99896
Load	80kgf	-0.01156	0.03271	0.99935
	90kgf	-0.02206	0.02371	0.99950
	110kgf	-0.03580	0.01631	0.99923
	120kgf	-0.04508	0.01413	0.99899
Pressure	190kPa	-0.02454	0.02216	0.99936
	200kPa	-0.02649	0.02062	0.99935
	220kPa	-0.02866	0.01794	0.99926
	230kPa	-0.03005	0.01678	0.99912
Speed	60km/h	-0.03062	0.01411	0.99952
	70km/h	-0.03192	0.01543	0.99939
	80km/h	-0.03061	0.01714	0.99940
	100km/h	-0.02499	0.02205	0.99919
Slip	0.13	-0.03837	0.01716	0.99891
	0.14	-0.03229	0.01818	0.99916
	0.16	-0.02412	0.02031	0.99949
	0.17	-0.02066	0.02139	0.99954

developed it, which can be found in References [3], [4], [5], and [6]. Thus, the evaluation of the estimation method can be performed using it. Figure 12 displays the hardware system employed in experimental platform, the sensors used to measure friction coefficient, and measurement page viewed on host computer.

The hardware system is mainly composed of mechanical system, hydraulic system, and electrical system. Among

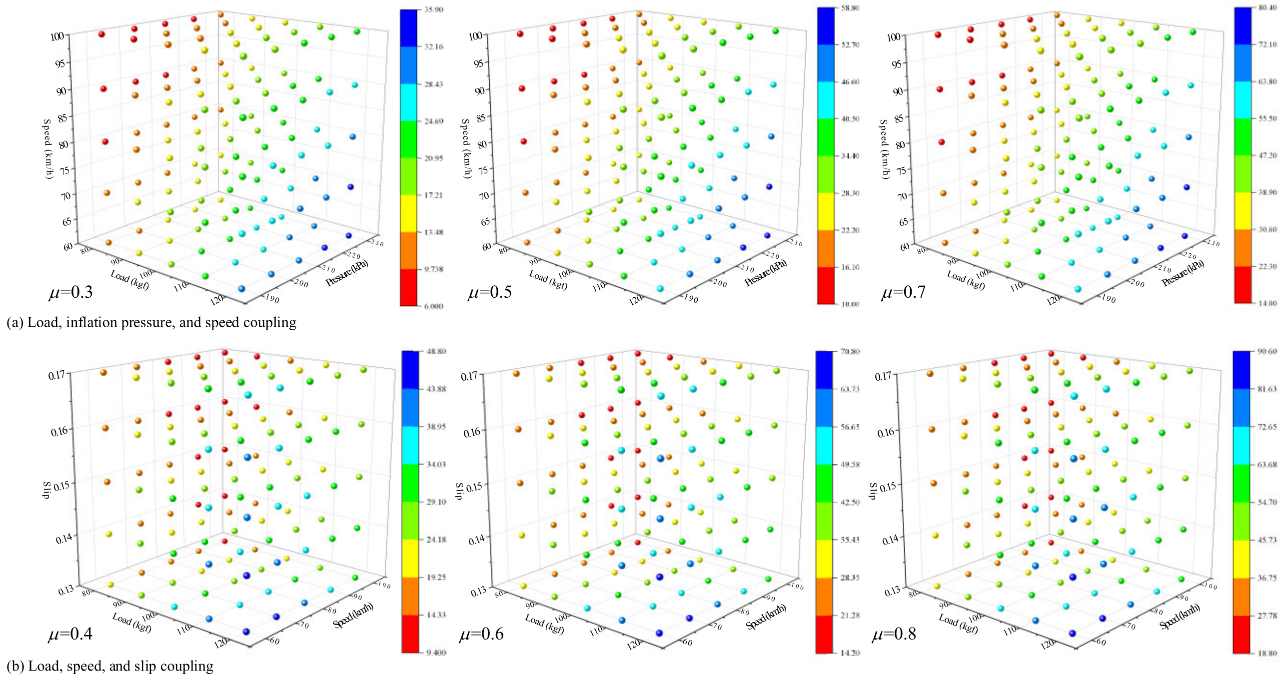

FIGURE 9. Frictional stress distribution with different working conditions (Coupling of three variables).

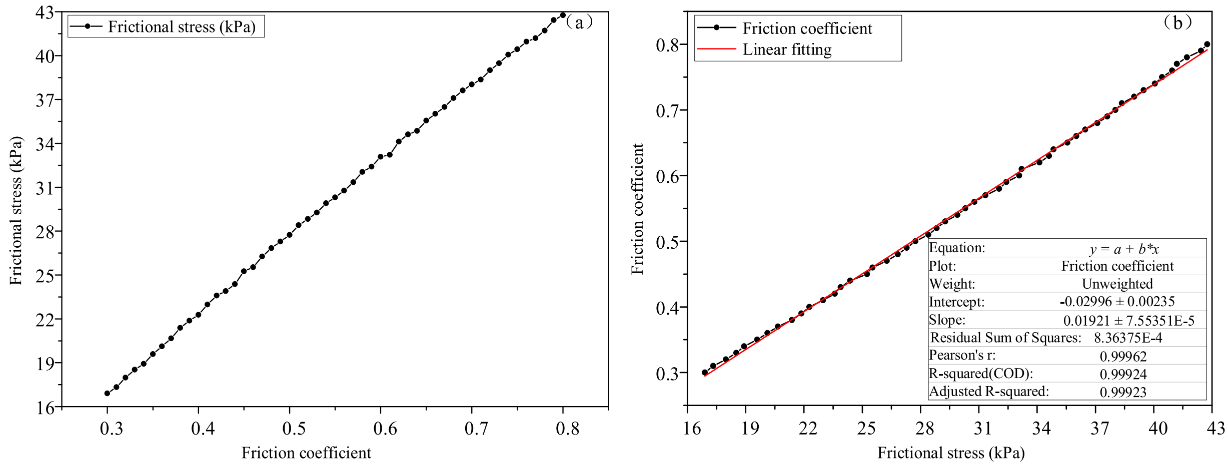

FIGURE 10. Corresponding relationship of curves with standard condition: (a) relationship between friction coefficient and frictional stress based on numerical analysis; (b) relationship between friction stress and friction coefficient using fitting.

them, the mechanical system ensures that measuring wheel produces a fixed slip rate; the hydraulic system is used for the measuring wheel's retraction and release; the electrical system consists of PLC and sensor system, which realizes control function in measuring process and data interaction function. The host computer is developed based on Microsoft Visual Studio platform, and Winform application is developed using C#. The program adopts multitasking and multithreading parallel processing, which can process a large amount of data efficiently.

C. VALIDATION AND DISCUSSION

Actual measurements were conducted with standard working condition using our constructed measurement platform, then the effectiveness of the estimation model was evaluated. An airport runway, with a length of 3000 m, was selected for measurement experiment, and the tread frictional stress is calculated using the ratio of tread friction to contact area. The curves, depicting six actual and estimated measurements, are illustrated in Figure 13.

Dividing the 3000m runway into 6 segments with a spacing of 500m, the average actual measurements of each segment are labelled as A_1 to A_6, while E_1 to E_6 for estimated measurements. Table 6 presents the results of the 6 measurements, while Figure 14 presents a comparison between actual and estimated measurements.

Table 6 and Figure 14 illustrate that the estimated measurements yield higher results than the actual measurements,

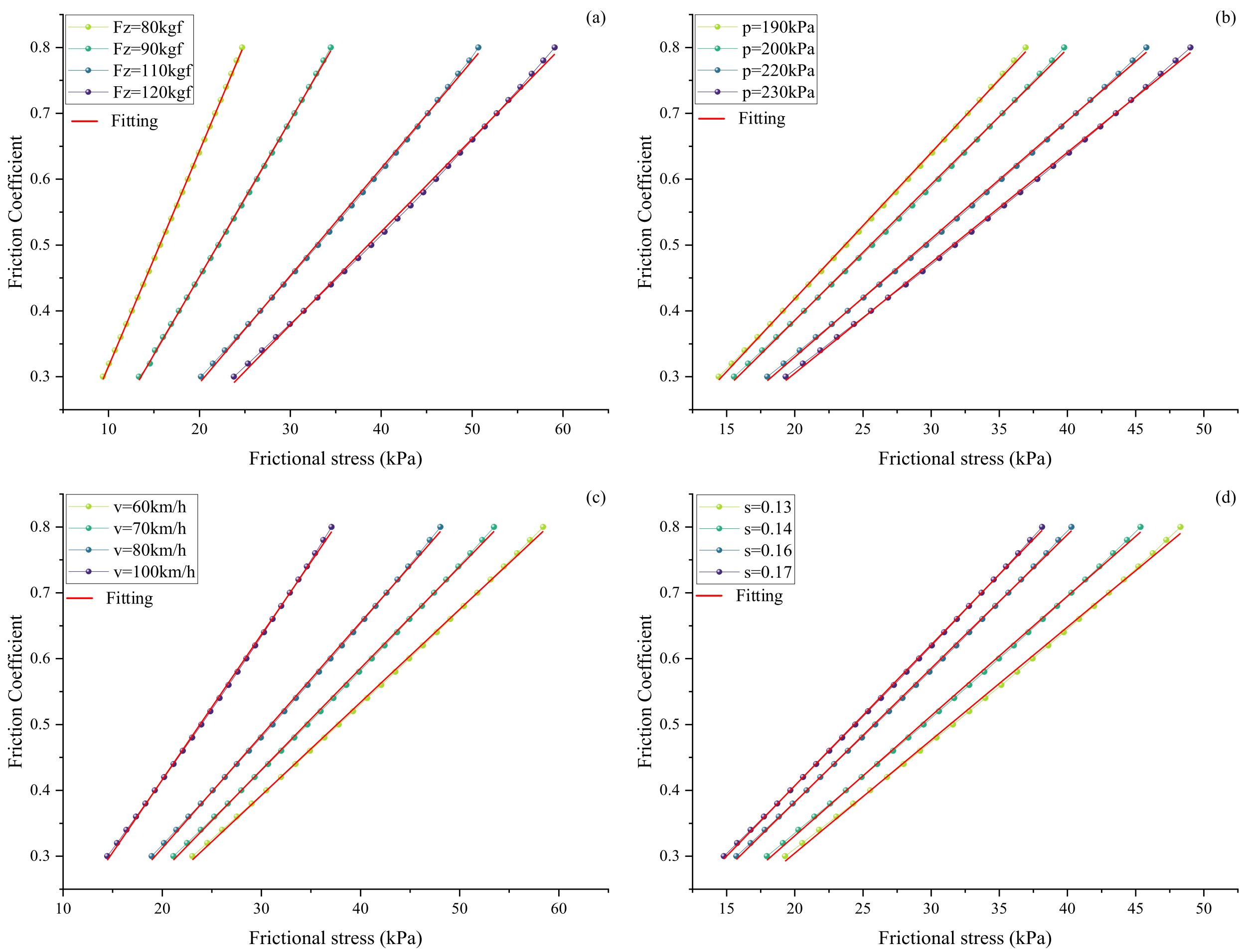

FIGURE 11. **Corresponding relationship of curves with other working conditions: (a) load; (b) inflation pressure; (c) speed; (d) slip.**

with an error range of 2.47% to 4.13%. Experimentation has effectively verified the validity and accuracy of the runway friction coefficient estimation method based on numerical analysis. The discrepancy between the two results can be attributed to:

1) Discrepancies exist between the tire rubber parameters used in numerical simulation and actual movement, as well as changes in parameters during real-time measurements that are not accounted for in estimation.
2) The numerical simulation employes a rigid runway surface instead of the actual, leading to potential differences in results.
3) During model construction, the maximum stress is used, but the estimation, only average stress is considered.
4) Tire parameters change continuously in small increments during actual measurements, but are kept constant during in estimations.

However, calibration method is applicable to enhance the precision of estimation measurement in applied engineering. This is achieved through the acquisition of correlation coefficients from numerous experiments.

D. COMPARISON WITH EXISTING METHODS

We propose a numerical analysis-based method for estimating runway friction coefficient, it achieves estimation solely based on tread frictional stress with specific working condition. Comparing this method to existing ones highlights its advantages and provides a basis for future improvements. Based on the related works in Section I, measurements can be classified into friction characteristic measurement and friction coefficient measurement based on the measurement targets.

Comparison with friction characteristic measurement. The caused-based method provides information related to friction measured by sensors. For example, References [16], [17], and [18] identifies the dry and wet state of the pavement through acoustic sensors, Ref. [20] assigns high, medium, and low friction characteristics to the pavement through optical sensor and algorithm, and Ref. [21] monitors tire slip rate through tire tread sensor. The numerical analysis method

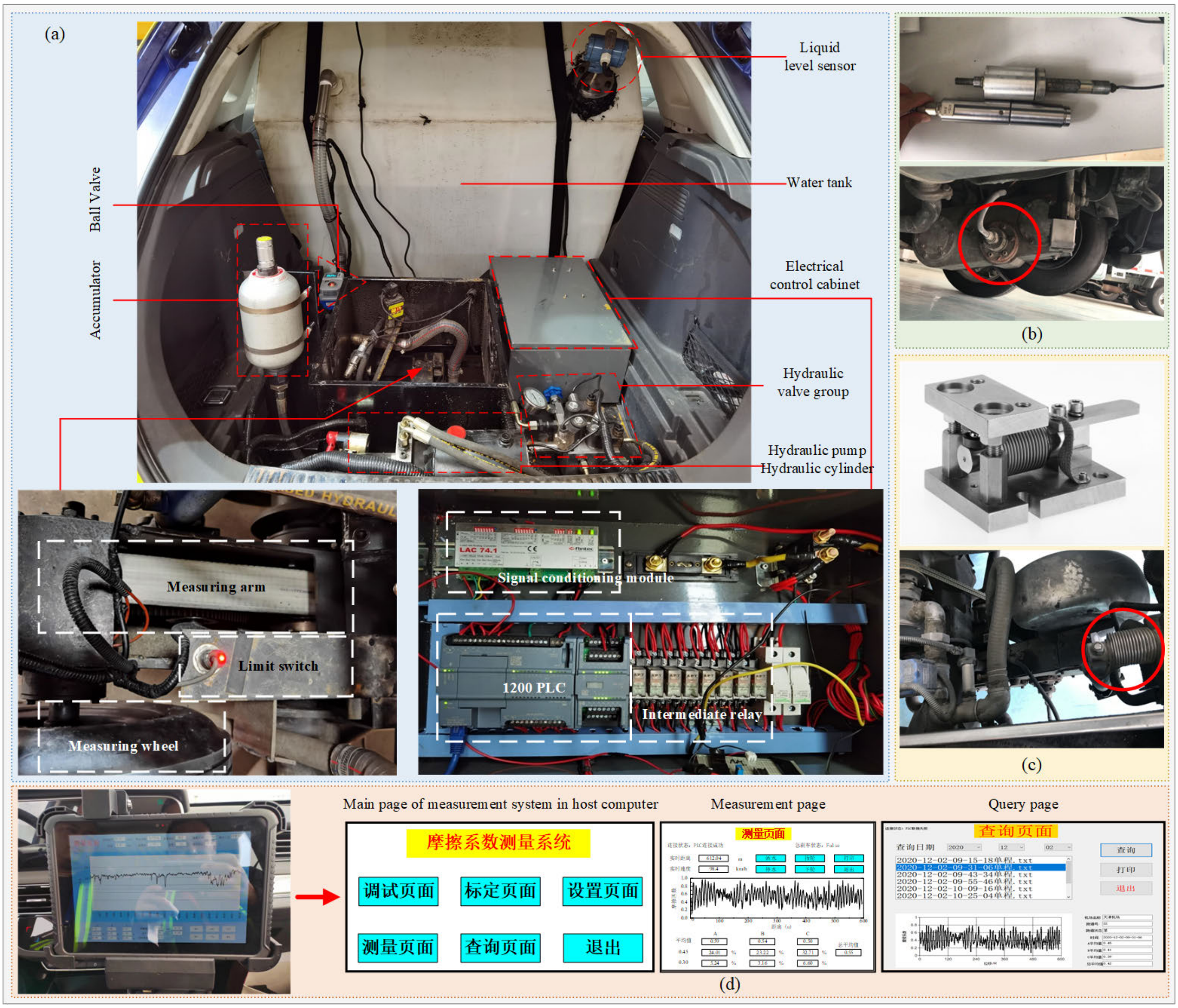

FIGURE 12. Friction coefficient measurement experimental platform: (a) overall layout; (b) horizontal force (friction force) sensor and installation position; (c) vertical force (load) sensor and installation position; (d) main pages in host computer (measurement equipment localization, pages in Chinese).

defines the friction coefficient on the contact surfaces and analyzes mechanical properties with different working conditions. By comparison, this paper proposes a method for measuring the friction coefficient, which is more useful for evaluating runway performance.

Comparison with friction coefficient measurement. Equipment-based method in Figure 1 shows that all four instruments can obtain the friction coefficient. Where, the measurement system described in this paper belongs to ASFT. In comparison to the other three devices, the method proposed in this paper can continuously measure the entire runway at a constant speed. For a comparison between the proposed method and actual measurements from the experimental system, refer to Figure 13, 14, and Table 6. Aircraft dynamics modeling method can indirectly solve the friction coefficient, but it requires making many assumptions and measuring many parameters. Influencing factor modeling method, such as References [11], [12], [13], and [14], requires fitting some empirical constants. The effect-based method requires consideration of different operating conditions and fitting empirical constants. Compared to the three methods, the method proposed in this paper only requires measuring the tread frictional stress to estimate the friction coefficient. Ref. [45] employs a neural network, which is a type of multi-source information fusion method, to estimate the maximum friction coefficient. The 15 experimental results indicate that the error between the estimation and actual measurement ranges from 2.29% to 12.19%. Meanwhile, the error between the estimation and actual measurement ranges from 2.47% to 4.13% proposed in this paper. By comparison, our proposed method has a smaller error range.

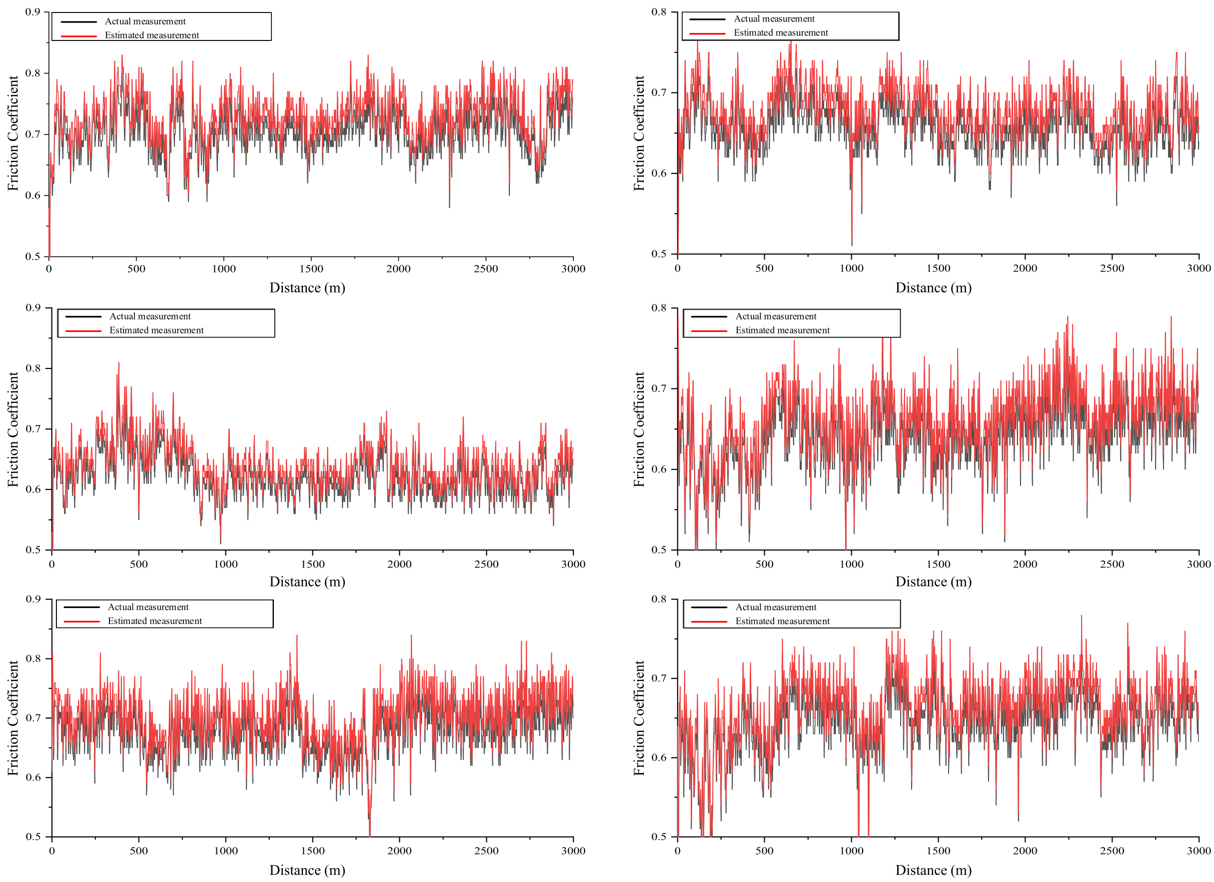

FIGURE 13. Actual and estimated measurement curves for friction coefficient.

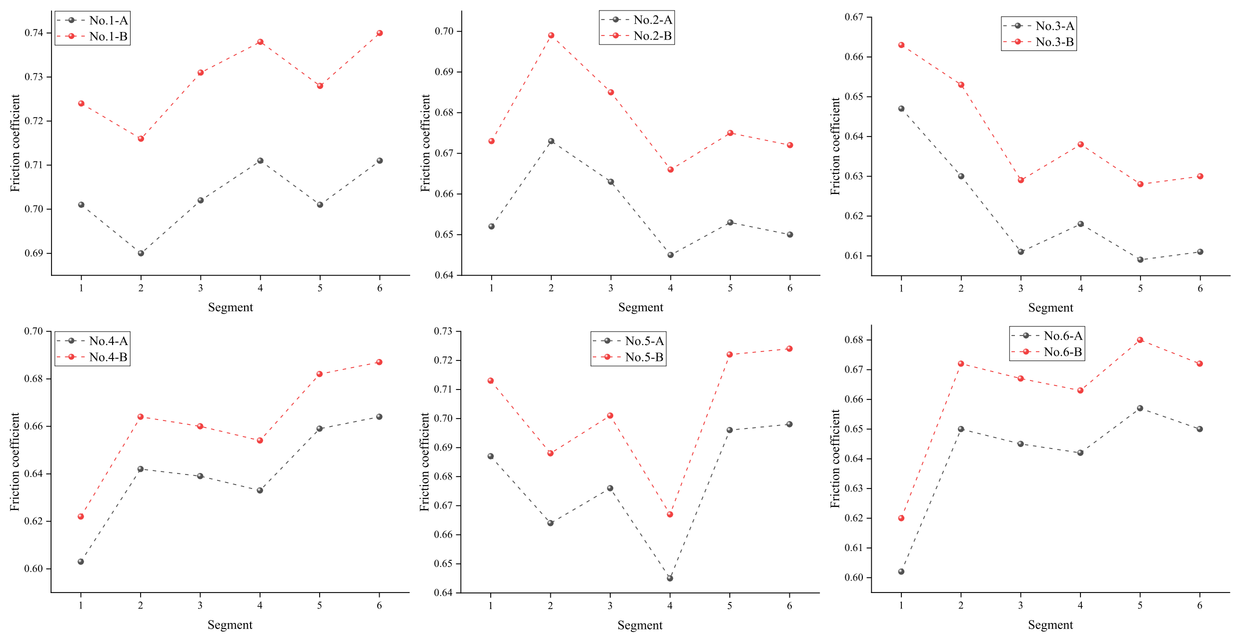

FIGURE 14. Comparison between actual and estimated measurements after segmentation.

In summary, our proposed method has the following advantages:

1) it measures friction coefficient rather than frictional characteristics;

TABLE 6. Actual and estimated measurement results.

	No.1	No.2	No.3	No.4	No.5	No.6
A1	0.701	0.652	0.647	0.603	0.687	0.602
E1	0.724	0.673	0.663	0.622	0.713	0.620
A2	0.690	0.673	0.630	0.642	0.664	0.650
E2	0.716	0.699	0.653	0.664	0.688	0.672
A3	0.702	0.663	0.611	0.639	0.676	0.645
E3	0.731	0.685	0.629	0.660	0.701	0.667
A4	0.711	0.645	0.618	0.633	0.645	0.642
E4	0.738	0.666	0.638	0.654	0.667	0.663
A5	0.701	0.653	0.609	0.659	0.696	0.657
E5	0.728	0.675	0.628	0.682	0.722	0.680
A6	0.711	0.650	0.611	0.664	0.698	0.650
E6	0.740	0.672	0.630	0.687	0.724	0.672

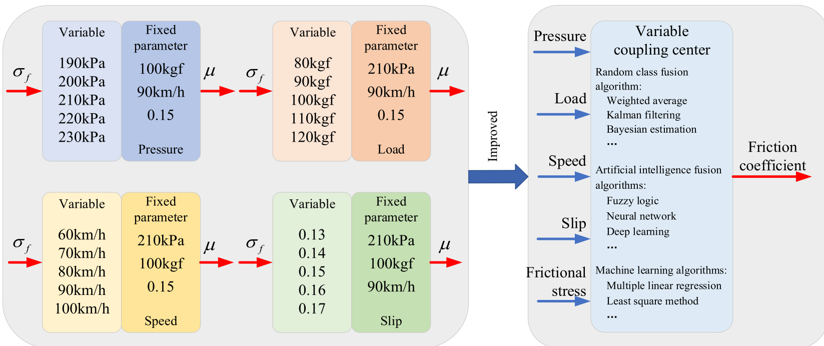

FIGURE 15. Conceptualization of future research work.

2) the estimation models have few empirical coefficients, and only requires the measurement of tread frictional stress to determine the friction coefficient;
3) the proposed method has been verified through a measurement experimental system, providing a basis for improving.

Of course, our proposed method also has shortcoming, as it is only applicable to estimating the friction coefficient with specific working condition. Therefore, in future research work, we have elucidated the efforts needed for the future.

VI. CONCLUSION AND FUTURE WORK

In order to study the measurement method of runway friction coefficient, this paper adopts several methods, including numerical analysis, estimation modeling, and experimental validation, to carry out an in-depth study. This paper proposes a finite element-based measurement method for runway friction coefficient, realizes the analysis of friction coefficient influencing factors, builds estimation models, and verifies the proposed method. Aiming at the influence of different tire motion parameters on friction, the relationship between the friction coefficient and frictional stress with different loads, inflation pressures, speeds, and slip rates is derived using ABAQUS finite element analysis. As the friction coefficient increases, the frictional stress increases; with the same friction coefficient condition, the larger the load and inflation pressure, the smaller the speed and slip, the larger the frictional stress. Using fitting reverse to solve the friction coefficient, establish estimation models for different working conditions, and achieve the method of estimating the friction coefficient solely based on the frictional stress with specific working conditions. The airport runway friction tester developed by our team is used to verify the estimation model, and the experimental results show that the error is between 2.47 and 4.13%, which proves the accuracy and effectiveness of the method. The research work in this paper can provide ideas for the research in the field of runway friction coefficient measurement method.

This paper combines various methods for pavement friction measurement and establishes estimation models with different working conditions through numerical analysis. However, it should be noted that these established estimation models are only applicable to specific working conditions. Therefore, in future work, the estimation models can be combined with the multivariate information fusion method to measure friction coefficient with any working conditions within a specific range. The concept is illustrated in Figure 15, allowing the 17 specific estimation models in this paper to be consolidated into one.

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