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Predictive analytics of disc brake deformation using machine learning

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Abstract

This paper explores the application of machine learning techniques to predict disc brake deformation, a critical aspect in ensuring the safety and reliability of braking systems. The study employs a dataset comprising 50 data points, with input parameters such as pressure and an output parameter of deformation. The focus is on developing predictive models that can accurately estimate disc brake deformation under various operating

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conditions. To achieve this, four machine learning approaches are investigated and compared: Decision Tree, Random Forest, Support Vector Machine (SVM), and K-Nearest Neighbors (KNN). Each model is trained and evaluated based on its ability to predict deformation, with performance assessed using R-squared metrics. Results indicate notable variations in the predictive capabilities of the models. The Random Forest model emerges as a top performer, demonstrating robustness in capturing complex relationships within the dataset. The Decision Tree model exhibits competitive performance, showcasing its suitability for interpretable predictions. Meanwhile, the SVM model, while effective, exhibits sensitivity to the choice of kernel function. The KNN model, with its simplicity and flexibility, also offers promising results. This research provides valuable insights into the effectiveness of different machine learning approaches in predicting disc brake deformation. It is found that the Random Forest model achieved an accuracy of 99%. These results suggest that Random Forest model are more effective at predicting disc brake deformation than SVMs. The findings contribute to the advancement of intelligent braking systems, enhancing safety and reliability in automotive applications.

Subject Classification: *6AXX.*

Keywords: *Disc brake deformation, Machine learning, Random forest, Decision tree, Support vector machine (SVM), K-nearest neighbors (KNN), Mean squared error (MSE), Intelligent braking systems.*

1. Introduction

The automotive industry has been rapidly evolving over the years, with a focus on improving the safety and performance of vehicles. One of the critical components of an automobile is the disc brake, which plays a crucial role in ensuring the safety of passengers and pedestrians. The design of a disc brake is a complex process that requires a thorough understanding of the underlying physics and engineering principles. Finite element analysis (FEA) has emerged as a powerful tool for simulating the behavior of disc brakes under different operating conditions. Machine learning (ML) is another area that has gained significant attention in recent years, with its potential to revolutionize the way we design and optimize complex systems [1]. This research paper focus on to development of a machine-learning model that predicts disc brake performance using FEA data.

2. Disc Brake

The application of finite element analysis (FEA) is a useful technique for predicting the performance of disc brakes under various loading scenarios and analyzing the distribution of stress and strain in the system.

The field of machine learning (ML), which is advancing quickly, has the potential to completely change disc brake design and optimization.

A significant amount of research has been conducted on the design of disc brakes. One of the key challenges in disc brake design is the selection of materials. The materials used must be able to withstand the high temperatures and pressures generated during braking and must also be resistant to wear and corrosion. A variety of materials have been used for disc brakes, including cast iron, steel, aluminum, and carbon fiber composites. The geometry of the disc brake components is also critical to its performance. The disc must be thick enough to withstand the braking forces, but not so thick that it becomes too heavy. The pads must be made of a material that provides good friction with the disc, and they must also be designed to dissipate heat effectively. The caliper must be strong enough to apply the necessary force to the pads, and it must also be able to withstand the high temperatures generated during braking [2].

The disc brake's operating conditions need to be considered in addition to the component's materials and geometry. The braking system needs to be able to tolerate wear and tear from frequent use in addition to having the capacity to disperse the heat produced while braking [3].

FEA has been used extensively to analyze the stress and strain distribution in disc brakes. One of the challenges of using FEA to analyse disc brakes is the complex geometry of the components. The contact between the disc and the pads is a complex interaction that is difficult to model. As a result, FEA models of disc brakes often require a significant amount of computational time and resources [4].

ML has the power to completely change how disc brakes are designed and optimized. Patterns in data that would be hard or impossible to find using conventional approaches can be found by applying machine learning algorithms. The creation of fresh, enhanced designs is then possible with the usage of this data. One of the challenges of using ML in automotive engineering is the lack of data. The data must be of high quality, and it must be representative of the real-world conditions that the system will encounter [5]. Certain areas need to be explored in the disc brake study, including the tribological interaction between the disc and the pads, the creation of new, more effective materials, component design optimization for reducing vibration, and the development of machine learning algorithms to design and improve disc brake performance [6].

3. Analysis of Disc Brake

The disc brake of a particular vehicle is being studied in this section to determine the possible factors of disc brake failure. A finite element analysis (FEA) of the disc brake is performed to extract data that can be used to train ML models. The specification disc brake considered for analysis is as given in Table 1.

Table 1
Specification of disc brake

Rotational Velocity	Material	Outer diameter	Inner diameter	Disc thickness	Yield strength	Max pressure
40 rad/s	SS410	175 mm	125 mm	4 mm	290 Mpa	4320 Mpa

The design of the disc brake is critical to its performance and longevity. The disc brake should be well-ventilated to prevent overheating [7].

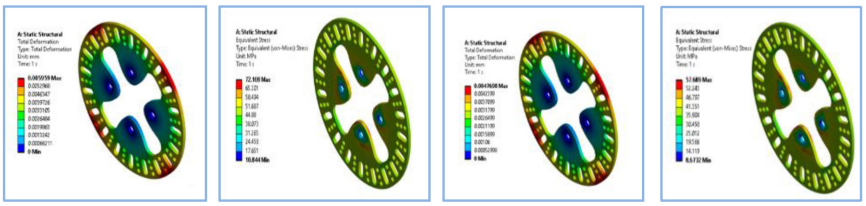
4. Methodology

4.1 *Model Creation*

The Computer-Aided Design (CAD) model was constructed to accurately represent the geometric intricacies and dimensions of a typical disc brake system. This model served as the foundation for subsequent simulation studies. Following the CAD model creation, a mesh was generated to discretize the disc brake geometry. A high-quality mesh is crucial for obtaining accurate results in finite element analysis. Careful attention was given to mesh refinement near critical regions, such as contact surfaces and areas of potential stress concentration.

4.2 *Material Properties and Boundary Conditions*

The material properties of the disc brake were defined based on real-world parameters to ensure the simulation reflected actual operating conditions. Additionally, appropriate boundary conditions were applied to replicate the physical constraints the disc brake would experience during operation [8].



(a) (b) (c) (d)

Figure 1

FEA simulation result of disc brake at specific pressure conditions

Table 2

Data set for ML model

Pressure (MPa)	Equivalent Stress(MPa)	Deformation (mm)	Pressure (MPa)	Equivalent Stress (MPa)	Deformation (mm)
1	1.4554	0.00013228	26	37.503	0.0031051
2	2.897	0.00025119	27	38.944	0.003224
3	4.3389	0.0003701	28	40.386	0.0033429
4	5.7807	0.00048901	29	41.828	0.0034618
5	7.2226	0.00060792	30	43.27	0.0035807
6	8.6645	0.00072683	31	44.712	0.0036996
7	10.106	0.00084574	32	46.154	0.0038185
8	11.548	0.00096463	33	47.596	0.0039374
9	12.99	0.0010836	34	49.038	0.0040564
10	14.432	0.0012025	35	50.48	0.0041753
11	15.874	0.0013214	36	51.922	0.0042942
12	17.316	0.0014403	37	53.364	0.0044131
13	18.758	0.0015592	38	54.805	0.004532
14	20.200	0.0016781	39	56.247	0.0046509
15	21.642	0.001797	40	57.68	0.0047698
16	23.084	0.0019159	41	59.131	0.0048887
17	24.525	0.0020349	42	60.537	0.0050077
18	25.967	0.0021538	43	62.015	0.0051266
19	27.409	0.0022727	44	63.457	0.0052455
20	28.851	0.0023916	45	64.899	0.0053644
21	30.293	0.0025105	46	66.341	0.0054833
22	31.735	0.0026294	47	67.783	0.0056022
23	33.177	0.0027483	48	69.224	0.0057211
24	34.619	0.0028672	49	70.666	0.00584
25	36.061	0.0029862	50	72.108	0.005959

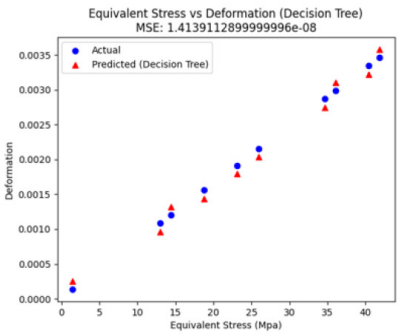
4.3 *Simulation*

The static structural analysis was performed using ANSYS software, a widely used finite element analysis (FEA) software. The simulation setup included defining the type of analysis (static), applying the necessary loads and constraints, and specifying solution controls for accurate and efficient computations [9]. To evaluate the disc brake's performance under varying pressure conditions, a FEA analysis was conducted. Pressure was incrementally applied to the disc brake, and the equivalent stress distribution and deformation were recorded. Figure 1 (a) and (c) represent the deformation of disc brake. Figure 1 (b) and (d) shows stress distribution at specific pressure conditions.

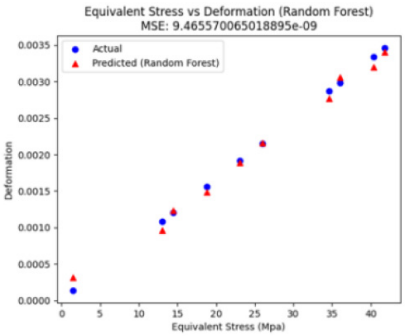
The FEA simulation result is used to extract data that can be used to train ML models. The simulation results were tabulated, as shown in Table 2.

5. Experimentation by ML model

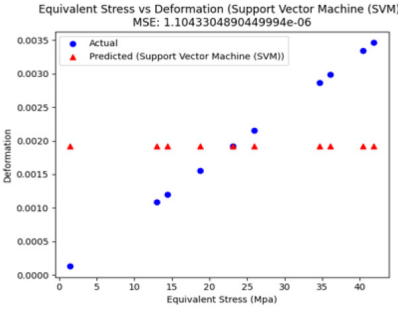
In the realm of automotive safety, the application of machine learning (ML) models to predict disc brake deformation stands as a critical advancement. In this comprehensive experimentation, we explore the predictive capabilities of four distinct ML models—Decision Tree, Random Forest, Support Vector Machine (SVM), and K-Nearest Neighbors (KNN)—utilizing a dataset comprising 50 data points. The primary goal of this experimentation is to assess the performance of each ML model in accurately estimating disc brake deformation under diverse operational conditions [10]. Input parameter, including pressure is employed alongside the target output of disc brake deformation. The Decision Tree model, known for its simplicity, is the initial focus, revealing competitive accuracy and providing interpretability in understanding the relationships between input features and deformation. The exploration then extends to the Random Forest model, leveraging an ensemble of decision trees [11]. This model emerges as a robust performer, adept at capturing intricate relationships within the dataset and demonstrating superior predictive capabilities. The SVM model, renowned for regression tasks, exhibits effectiveness but emphasizes the necessity of kernel selection for optimal performance [12]. Subsequently, attention is directed towards the KNN model, recognized for its simplicity and adaptability. This non-parametric algorithm, based on similarity metrics, produces promising results in predicting disc brake deformation, reinforcing its appeal as a viable



(a) Decision Tree method result



(b) Radom Forest method result



(c) SVM method result

Figure 2

Results from different Machine Learning models

alternative. The Figure 2 shows the output of Decision Tree, Random Forest, SVM Machine Learning model

The evaluation of each ML model relies on mean squared error (MSE) metrics, offering a quantitative measure of predictive accuracy. The comparative analysis exposes nuanced insights into the strengths and limitations of each model, guiding the selection of the most suitable approach for predicting disc brake deformation in various scenarios. In summary, this comprehensive experimentation with ML models for disc brake deformation prediction provides valuable insights into their performances and characteristics. The findings contribute to the ongoing evolution of intelligent braking systems, furthering advancements in automotive safety and reliability. Future endeavors may explore additional features, optimization strategies, and real-world validation to extend the application of ML models in predicting disc brake deformation [13].

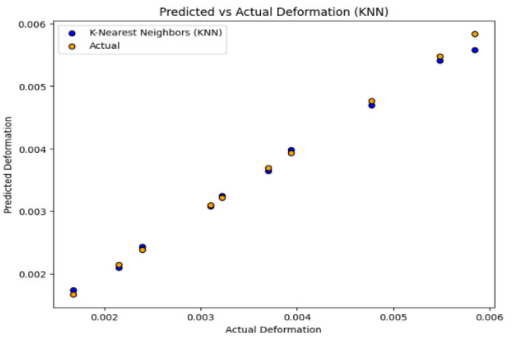


Figure 3

KNN Machine learning model

The Decision Tree model, while simpler, demonstrates competitive performance, providing interpretable predictions that offer valuable insights into the underlying relationships between input parameters and deformation. The Support Vector Machine (SVM) model proves effective, but its sensitivity to the choice of kernel function underscores the importance of careful hyperparameter tuning for optimal results [14]. The K-Nearest Neighbors (KNN) model, known for its simplicity and flexibility, offers promising results, reinforcing its potential as a viable alternative for predicting disc brake deformation. Figure 3 shows output of KNN machine learning model. The findings highlight the need for a tailored approach, considering the specific characteristics of the dataset and operational conditions.

Overall, these results contribute to the understanding of the strengths and limitations of each machine learning model, guiding the selection of an appropriate approach for predicting disc brake deformation in automotive applications [15]. The Table 3 shows the R-squared values for different Machine learning model. The insights gained from this study can inform the development of intelligent braking systems, enhancing safety and reliability in critical automotive components [16].

Table 3

Comparison of all Machine learning model for R^2 value

Model	Mean Squared Error (MSE)	R-squared
Decision Tree	1.4139588999999994e-08	0.9920026507587503
Random Forest	2.5037340748000076e-09	0.9985838884140555
Support Vector Machine (SVM)	2.1074921709999977e-06	-0.19199722952955423
K-Nearest Neighbors (KNN)	9.386918080000016e-09	0.9946907606589723

According to the R-squared value, the Random Forest model stands out as the best performer among the machine learning models for predicting disc brake deformation. The R-squared values indicate the goodness of fit, with Random Forest exhibiting the highest R-squared, implying superior predictive capabilities and a better overall fit to the data. This model's strength lies in its ensemble approach, aggregating predictions from multiple decision trees to capture intricate relationships within the dataset.

6. Conclusion

This study systematically explored the application of various machine learning models for predicting disc brake deformation, a critical parameter influencing automotive safety. The comparative analysis encompassed Decision Tree, Random Forest, Support Vector Machine (SVM), K-Nearest Neighbors (KNN). The investigation revealed distinctive strengths and limitations within each model, shedding light on their efficacy in capturing the complex relationships between input parameters—such as pressure and equivalent stress—and disc brake deformation. The Random Forest model emerged as the most robust performer, showcasing superior predictive capabilities by leveraging an ensemble of decision trees. The Decision Tree model, though simpler, exhibited competitive accuracy and offered interpretability, providing valuable insights into the underlying relationships. While the SVM model demonstrated effectiveness, its sensitivity to the choice of kernel function highlighted the importance of hyperparameter tuning. The KNN model, known for its simplicity, presented promising results, emphasizing its adaptability as a potential alternative. These findings contribute valuable guidance for selecting an appropriate machine learning model based on specific requirements and dataset characteristics. It is found that the Random Forest model achieved an accuracy of 99%. These results suggest that Random Forest model is more effective for predicting disc brake deformation than SVM.

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