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Topological Optimization For Reliability Analysis Of Automotive Wheels Via Impact And Bending Fatigue Tests

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Keywords ：Aluminum wheel, Topological optimization, Reliability analysis, Impact test

ABSTRACT

Being one of the key rotating components of an automobile, the lightweight design and reliability of the wheel directly impact the overall performance of the automobile. When optimizing the lightweight design of the entire wheel system, it is crucial to consider how structural changes affect its fatigue performance, impact resistance, and other mechanical properties. Therefore, a reliability-based lightweight design method is employed to optimize the racing wheel system, ensuring it meets the performance requirements of automobile while shortening the design process and providing a comprehensive optimization scheme. A parametric model of the wheel system is established using data from the participating automobile, and mechanical analysis of the designed wheel is performed through finite element methods, subsequently leading to topological optimization based on the results. The fatigue life is assessed through impact and bending fatigue tests, determining whether the designed wheel system meets the necessary performance criteria and providing theoretical support for wheel design and practical applications in the participating automobiles. This method is also applicable to the lightweight design of other mechanical components.

INTRODUCTION

During the operation of the wheel system, the wheel experiences not only multi-directioal movements and rotation around the hub center but also various complex forces, such as torsional forces, impact forces from the road surface, and shear forces acting on the spokes during braking. Correctly estimating the fatigue strength of components is fundamental for designing many parts (Balthazar et al., 2007; Deng et al., 2024; Rasul et al.,2024; Gharaibeh et al., 2024). Since wheels are part of the unsprung mass, reducing their weight has a much greater impact on automobile performance compared to reducing the weight of the sprung mass, leading to significant improvements in overall automobile performance.

In lightweight suspension design, automotive engineers use various methods to estimate stresses and fatigue in suspension systems during the analysis phase (Sindhwani et al., 2021; Yang et al., 2023). The design and analysis of racing suspension systems mainly involves kinematic and dynamic analysis of suspension components (Saurabh et al., 2016). In order to optimize vehicle performance, a multi-body model was developed using computer-aided design (CAD) and MathWorks' Simscape multi-body simulation environment (Celenta et al., 2024). Moreover, the geometric parameters of the trailing arms, elastic and damping elements were determined based on the tire characteristics and subsequently a dynamic model of the suspension system was created (Liang et al., 2018).

Lightweight materials have great potential for reducing automotive fuel consumption and emissions (Gonçalves et al., 2022). In wheel design, weight reduction can be achieved effectively through the introduction of new materials, either in the form of single or multiple materials (Kaluza et al., 2017). Various materials, including magnesium alloys, have been explored for wheel construction (Somayaji et al., 2022). To establish a reliable basis for the fatigue-resistant design of magnesium alloy wheels, strain-controlled fatigue tests were conducted on specimens from the rims and discs of extruded AZ80 wheels (Jiang et al., 2018; Jiang et al., 2023). Furthermore, the use of lightweight composite rims with higher stiffness can help to further reduce wheel weight (Zhao et al., 2020; Andukuri et al., 2022). The application of carbon fiber reinforced composites and structural steel

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in lightweight wheel designs has been compared and analyzed (Wang et al., 2021), and the injection molding process for carbon fiber composite wheels with complex shapes was numerically investigated (Gardie et al., 2021). In some designs, Aluminum 7079 alloy reinforced with 8% carbon fiber (CF) was also used as an optimized material (Huang et al., 2019). Aluminum alloys are commonly used for manufacturing alloy wheels based on cost considerations and offer a higher strength-to-weight ratio as well as better thermal conductivity compared to steel wheels (Shinde et al., 2022).

When the vehicle is driven aggressively, the wheels are subjected to higher loads, making lightweight design even more critical for improving overall vehicle performance. The combination of bending stresses, torsional shear stresses, and axial stresses can result in the formation of cracks, which propagate during testing and can ultimately lead to catastrophic wheel failure (Shinde et al., 2021). After structural modifications, impact and fatigue analysis tests are conducted on the wheels to verify their reliability and flexural fatigue life, ensuring compliance with required performance criteria. Predicting the fatigue strength of the material is essential before conducting fatigue life analysis (Liu et al., 2022). Plastic deformation plays a significant role in enhancing the fatigue strength of aluminum alloys by refining grain structures, inducing residual compressive stresses, and increasing dislocation density through strain hardening. These effects delay the initiation and propagation of fatigue cracks, improving overall fatigue performance. However, the impact of plastic deformation depends on factors such as deformation uniformity, temperature, and process conditions, as non-uniform deformation can lead to stress concentrations that reduce fatigue resistance. In applications like wheels, the characteristic load spectrum for fatigue life prediction must account for variations in mechanical properties caused by plastic deformation, ensuring reliable performance under cyclic loading.In the next article on optimising wheel systems, it will be discussed whether it is appropriate to introduce areas of plastic deformation to improve overall performance.(Zhang et al., 2023). Typically, stress and strain analysis is performed using the finite element method, and fatigue life is then predicted based on the maximum stress experienced according to the product (Tong et al., 2017). Under cyclic loading, fatigue damage is the primary failure mode of mechanical components, with high-cycle fatigue being the most common (Wang et al., 2019; Zhang et al., 2019; Ammar et al., 2008; Raju et al., 2007; Yang et al., 2024). Neuber stresses are calculated from pseudoelastic results using linear elastic finite element analysis (Raju et al., 2016). Additionally, probabilistic and interval reliability analyses are used to determine reliability indices, and the effect of parameter types on reliability indices is evaluated (Liu et al., 2021; Luo et al., 2024; Meng et al., 2024; Meng et al., 2024).

Impact testing of wheels is necessary at high speeds, as the wheels are constantly subjected to impact loads from the road surface (Liu et al., 2021). The flexural strength, radial fatigue strength, and impact performance of bolted wheels were analyzed at both 13 and 90 degrees. A comprehensive multi-objective optimization of structure, connection, and performance was conducted for fatigue and impact performance (Xu et al., 2022). The 90-degree wheel impact test was used to simulate severe driving conditions, such as frontal impacts caused by potholes on the road (Gao et al., 2019). An equivalent strain model was developed to predict fatigue life, considering the effects of average strain and stress under asymmetric loading cycles (Zhi et al., 2024). A 13-degree impact test was employed in some studies to evaluate an 18-inch hybrid wheel, consisting of an aluminum alloy disc and a composite rim, to provide design basis data for assessing wheel performance (Previati et al., 2019). Furthermore, radial impact tests on various aluminum wheels can be simulated using finite element models to evaluate their performance (Hwang et al., 2018).

Topology optimisation is of paramount importance for the lightweight design of wheels. A structural topology optimisation method has been proposed for the design, optimisation and additive manufacturing of highly stressed turbomachinery components, such as turbine blades (Pinelli et al., 2022). In order to enhance the impact resistance of wheels made from lightweight materials, topology optimisation (TO) models for multiple design spaces and loading scenarios were combined with grey relational analysis (GRA) and principal component analysis (PCA). This integration was achieved through the creation of a multi-objective topology optimisation (MOTO) method, which resulted in the development of an optimised wheel topology layout (Zhang et al., 2021). Machine learning (ML) is a field of study that is transforming the realm of topological optimisation. By enhancing reliability through efficient computation and uncertainty management, ML is driving innovation in this domain. The utilisation of predictive models, such as neural networks, enables the acceleration of performance evaluation, thereby reducing the reliance on time-consuming finite element analyses. (Wang et al., 2024; Peng et al., 2024; Mishra et al., 2024)Furthermore, a multi-objective topology optimisation method for steel wheels, which considers compliance and intrinsic frequency as static and dynamic optimisation objectives, has also been applied for lightweight design (Xiao et al., 2014).

From an assembly perspective, it is essential to make disassembly and reassembly straightforward. For formula racing , post-design training is as crucial as the initial design itself, so ease of assembly and maintenance should be integrated into the early design stages. With four dynamic events in the competition, each emphasizing different evaluation criteria, adjustments to the automobile must be made to align with the focus of each event.

WHEEL DESIGN AND ANALYSIS

A wheel design tailored to meet the team's requirements is presented, integrating data from participating automobiles and analyzing common causes of racing accidents. The reliability of the design is validated through static analysis, topological optimization, impact testing, and bending fatigue testing, providing a robust theoretical foundation for manufacturing new racing wheels.

The wheel design and analysis process is illustrated in Figure 1:

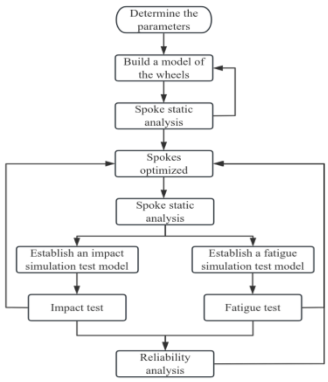


Fig. 1. Flow chart of wheel design and analysis

In the above process, a structured approach is provided for the design and analysis of the wheel system. After completing the modeling, an initial simulation analysis can be used to preliminarily verify the feasibility of the design concept. If feasible, topological optimization is performed on the initial model based on the analysis results to achieve lightweight goals. After completing topological optimization, a static analysis is conducted again to evaluate its mechanical performance and provide appropriate feedback. If the design does not meet usage standards, further optimization is carried out according to the topological results; if it meets the required standards, impact and fatigue tests can be conducted in a similar manner to the previous steps. Finally, a reliability analysis of the designed wheel system is performed, with iterative adjustments made to obtain a complete wheel system.

A similar design process can be applied to other components of the automobile, aiming to use minimal material to create lightweight, highly reliable parts. For components that are prone to wear or require frequent replacement, this approach allows for enhanced reliability or easier disassembly and replacement through optimized design. This reliability-based design method can also be extended to other mechanical parts, accelerating the design process overall.

Design of racing wheels

Based on data from the participating automobiles and competition requirements, this wheel system design uses a split-wheel structure, primarily consisting of two components: the rim and the spoke. The rim's function is to support the tire, the spoke connect the rim to the hub, support the axle, and transfer loads. Generally, spokes are categorized as either solid spoke plates or spoked types. The spoke is connected to the automobile's hub through a centering hole.

Another crucial aspect of the wheel system design is ensuring effective brake disc heat dissipation. Formula tracks feature numerous turns, with combination corners being the most common. To enhance braking and overall automobile safety in these corners, it's essential to prevent brake disc overheating during extended, intense driving to avoid brake failure. The wheel system design must support adequate brake disc cooling and ensure that the spokes do not obstruct heat dissipation.

Wheel assembly modeling

The spokes and rim of the wheel are connected with eight M8×15 bolts, positioned at 45° intervals between the bolt holes. The spokes are attached to the hub via cylindrical pins, each with a diameter of 10 mm and a length of 13 mm, totaling 11 pins.

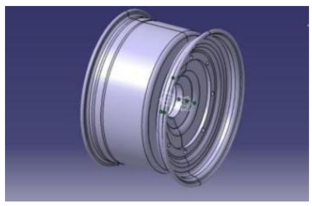


Fig. 2. Wheel assembly

Finite Element Analysis

The finite element analysis of the wheel utilizes a bilinear dynamic hardening model, which represents the material's stress-strain curve using two straight lines with different slopes. Once the stress surpasses the yield point, the material enters the plastic deformation stage, and if loading continues, the slope of the line will adjust accordingly.Compared to elastic-plastic and non-linear hardening models, the bilinear model is easier to parameterize and implement but lacks precision in capturing complex strain-hardening behaviors and localized phenomena like necking. While it is less accurate than non-linear or viscoplastic models for applications requiring detailed strain-rate sensitivity or large plastic deformation, it is sufficient for many engineering applications, striking a balance between accuracy and practicality.This model simplifies the true stress-strain behavior of aluminum alloy and incorporates yield criteria, flow criteria, and kinematic hardening criteria, making it suitable for the finite element analysis of the designed wheel.

Material definition

The density of the aluminum alloy is lower than that of structural steel, offering significant advantages in terms of lightweighting. Additionally, its excellent thermal conductivity enhances heat dissipation.Which is particularly beneficial for wheels and related systems. Therefore, aluminum alloy has been selected as the wheel material. This alloy has a Young's modulus of 73800MPa, a Poisson' s ratio of 0.337, and a density of 2.77 kg/m^3.

Static analysis

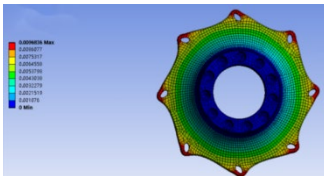
After completing the three-dimensional modeling of the wheel and selecting the model for finite element analysis, a static analysis can be conducted to determine whether the wheel's mechanical properties meet the required standards. For the wheels of a Formula Racing, the working condition limits are high. The steering-braking condition is selected as the critical load case when applying loads. The parameters of the automobile are as follows:

(1) The total weight of the driver and automobile distributed to each wheel is 490 N.

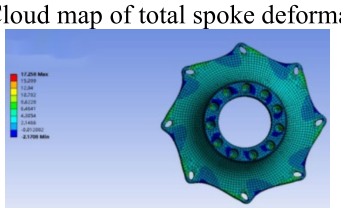
(2) The bending moment on the wheel is: 456741 N · mm.

(3) The braking torque on the wheel under braking conditions is: 495332 N · mm.

In the static analysis, we applied 1000 N pressure to the end face of the hub bearing, and applied brake torque to the contact between the spoke and the rim bolt. The analysis results are as follows:



(a) Cloud map of total spoke deformation



(b) Spoke stress cloud

(c)

Fig. 3. Results of static analysis

After analyzing the maximum deformation produced in the spokes when subjected to the applied load at the 8 bolts, the maximum deformation is 0.0097 mm, and the maximum stress of the parts in the limit working condition is 17.258 MPa. The environment of the Formula race is a closed field, with the driving surface made of asphalt, and the event organizing committee limits the flow restriction valve diameter to 20 mm. The results obtained from this static mechanical analysis and hydrostatic analysis exceed the actual use requirements. Therefore, the wheel can be optimized and improved.

Improved spoke design

The design of the rim has to be combined with the tire size and ensure its airtightness, so there is not much room for improvement. The main focus is to analyze the spokes to achieve the goal of lightweighting.

Combined with the completed hydrostatic analysis, this improvement uses topology optimization, in which the optimal distribution of materials in the structure is determined through calculation of boundary conditions within a given design region to reduce mass, with a target weight reduction of 35%. The results after topology optimization are as follows:

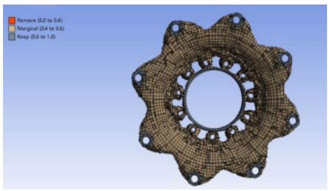
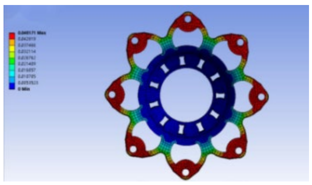


Fig. 4. Diagram of topology optimization results

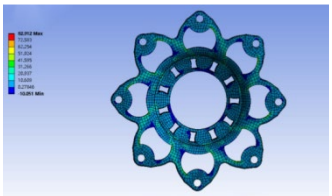
After completing the topology optimization of the wheel spokes, it is determined where they can be improved. The modifications are mainly at the bolted connection between the spokes and the rim. The spokes can be skeletonized at the interface between the spokes and the rim, and skeletonization can also be applied to the spoke disk. The obtained results are as follows:

Fig. 5. Improved rear spoke 3D model

After topology optimization, the new model is subjected to static analysis to ensure that its mechanical properties are not degraded due to structural changes under the extreme working conditions in the competition. The following are the results of the static analysis:



(a) Spoke global deformation cloud image



(b) Global stress cloud map of spoke

Fig. 6. Static analysis results after optimization

After the static analysis, the maximum deformation of the spokes under the limit working conditions is 0.0481 mm, and the maximum stress is 82.921 MPa. The preliminary judgment is that it meets the usage requirements.

FATIGUE TEST ANALYSIS OF WHEEL

Impact test

The impact test simulates the external impact forces on the 's wheels during driving (Wan et al., 2019). According to GB/T 15704-2012, the ground was set to an angle of 13° ± 1°. To ensure complete contact between the impact rigid block and the rim, the punch was designed to overlap the rim by more than 25 mm. Through simulations of sudden high-energy impacts, the material and structural resistance to crack propagation and catastrophic failure was assessed.

Material definition

Table 1. Definition of Material Properties and Related Parameter

Material Name	Density	Elastic Modulus	Poisson's Ratio
Aluminum alloy	2.77×103	71000	0.33
Steel	7.829×103	206940	0.288

Define the falling velocity and the initial velocity of the falling impact block, Eq:

$$V^2 = 2g(230 - h) \quad (1)$$

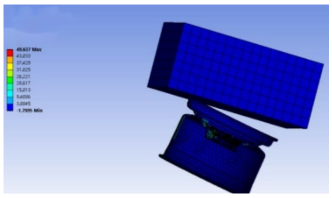
where h is the distance from the center of the bottom surface under the initial position of the impact block to the highest point of the rim model.The height of the block is 142 mm and the velocity of the block in contact with the wheel is calculated to be 1.313 m/s. To simplify the calculation the impactor moves at a constant velocity of 1.313 m/s during its fall. The spokes and rim are connected in a binding type to ensure that no relative displacement occurs during the impact.

The mass of the impact block is calculated as:

$$D = 0.6W + 180 \quad (2)$$

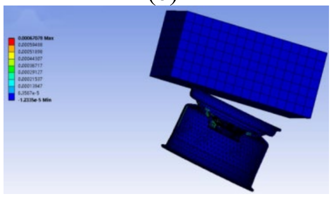
Where W is the mass of the wheel load calculated as 50 kg.

The results of the analysis are as follows:



(a) Overall stress nephogram of impact test

(b)



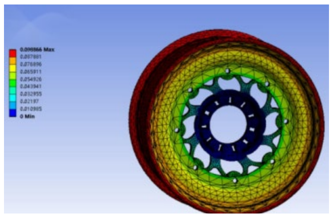
(c) Cloud map of total wheel deformation

Fig. 7. Impact test analysis results

After analyzing the conclusions of the rim impact test, in which the maximum deformation is 69.37 mm and the maximum stress on the wheel is 48.637 MPa, it is noted that the entire impact test process lasts a total of 40 milliseconds, in 0.3 milliseconds to reach the rim to withstand the maximum stress.

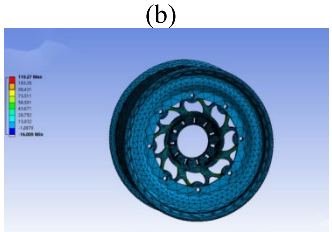
Wheel bending fatigue test

The wheel bending fatigue test can simulate the stress conditions of the wheel rim when the racing automobile is running at high speed, allowing for the detection of the fatigue performance of the wheel rim. According to GB/T 5334-2021, the wheel was clamped using a fixture to secure it to the test bench. Five M18 bolts were used to attach the wheel to the loading shaft via its spokes. During testing, a load was applied at the end of the shaft, and a motor was employed to rotate the assembly around the axis, generating centrifugal force. This subjected the wheel to a rotating moment, enabling an analysis of its bending fatigue.



(a) Cloud map of total wheel deformation

(b)



(c) Nephogram of total wheel stress

Fig. 8. Results of static analysis

The analysis shows that the maximum deformation of the wheel under the limit working condition is 0.09 mm and the maximum stress is 118.27 MPa, which meets the requirements of use.

Fatigue life analysis

Fatigue life is commonly expressed using N, which reflects the number of cycles of stress or strain experienced before fatigue failure occurs. The fatigue life of a specimen depends on its strength and the relevant mechanical properties of the applied stress.The relationship between the external stress levels and the standard specimen is represented by a curve known as the material's S-N curve.

The S-N curve (stress-life curve) relates the applied stress amplitude to the number of cycles to failure, making it simple to use, particularly when material-specific S-N data are available for design and engineering. This method is especially effective in predicting high-cycle fatigue, which occurs after a large number of cycles at lower stress amplitudes, typically without significant crack initiation and propagation phases. Complementary models, such as the Paris-Erdogan crack growth model, are often employed when crack propagation is significant, when low-cycle fatigue predominates, or when more detailed local analyses are required. Considering the requirements of wheel design, the S-N curve is therefore chosen.

For aluminum alloy material, its fatigue limit S_f corresponding to the number of cycles, is generally $N = 10^7$ times, which is calculated as follows:

when $N = 10^6$

$$S_{10^6} = S_f = kS_u \tag{3}$$

It can be concluded that:

$$C = (0.9S_u)^m * 10^3 = (kS_u)^m * 10^6 \tag{4}$$

Where $k = 0.5, S_u = 240\text{MPa}$

$$S^{3/\lg(0.9/0.5)}N = \{(0.9 \times 240)\}\text{^}(3/\lg(0.9/0.5)) \times 10^6 \tag{5}$$

The S-N fatigue curves of the selected aluminum alloy materials can be obtained, and the following figure is presented through fitting(Burhan et al., 2016).

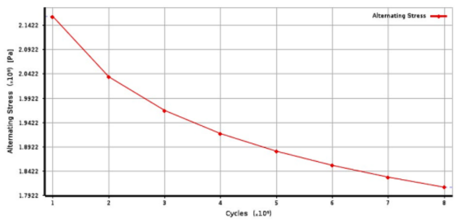
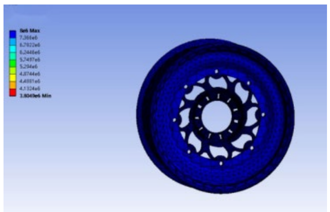
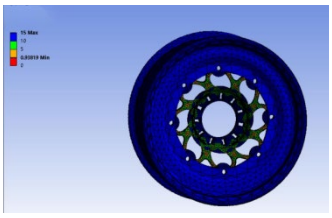


Fig. 9. S-N fatigue curve of aluminum alloy

The design life is adjusted to 10^6 times for fatigue calculation and the results are as follows:



(a) Wheel bending fatigue life



(b) Wheel bending fatigue coefficient

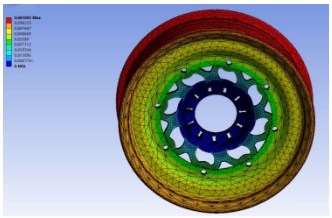
Fig. 10. Fatigue test results

From the results of the analysis, it is clear that the minimum life of the wheel is more than 3.8×10^6 times, and the minimum safety factor on the wheel spokes is about 0.93. Its safety factor does not meet the usage requirements, and the structure needs to be modified.

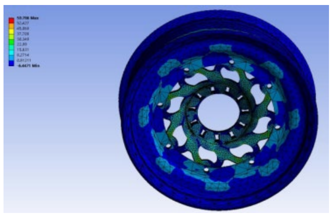
Improved wheel spoke and analysis

As the design was too lightweight, resulting in spokes that were prone to failure, the spoke cut-outs were adjusted and modified, with the original distance between the two arcs being revised from 35.30 mm to 29.34 mm, and the radii of the rounded corners of the spokes, which were all originally 1 mm, being revised to a radius of 2 mm.The results of the analysis are as follows:

Static analysis



(a) Cloud image of overall wheel deformation



(b) Overall stress cloud map of wheel

Fig. 11. Results of static analysis

After static analysis, the following conclusions are obtained: the maximum deformation of the wheel under the limit working condition is 0.061 mm, and the maximum stress value is 58.786 MPa.

Fatigue analysis

After the completion of the static analysis, the wheel needs to undergo bending fatigue analysis once again to verify its reliability and ensure that it will not fail in motion. The analysis results are as follows:

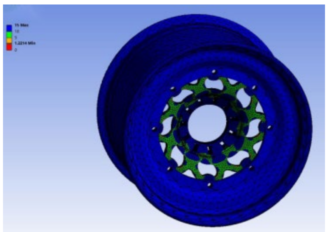


Fig.12. Wheel bending fatigue coefficient

The safety coefficient of the modified wheel is analyzed to be 1.224, which meets the usage requirements. The mass of the modified wheel is 2.06 kg, and the mass of the original wheel is 2.215 kg, resulting in a 6.7% weight reduction of the wheel individually and a 26.8% overall weight reduction.

Impact reliability Analysis

According to the statistical law governing the load and strength of a part under a given working condition, the stress and strength ‘interference’ model is used to predict the strength of the part, thereby determining its reliability. In the impact test of the wheel, assuming that the stresses are normally distributed, the reliability model of the wheel is as follows:

$$f(S) = \frac{1}{\sqrt{2\pi}\sigma_s} \exp\left[-\frac{1}{2}\left(\frac{S-u_s}{\sigma_s}\right)^2\right] \quad (6)$$

$$g(\delta) = \frac{1}{\sqrt{2\pi}\sigma_\delta} \exp\left[-\frac{1}{2}\left(\frac{S-u_\delta}{\sigma_\delta}\right)^2\right] \quad (7)$$

where $y = \delta - S$ is defined, so the random variable y is normally distributed, and its mean and standard deviation are respectively:

$$u_y = u_\delta - u_s \quad (8)$$

$$\delta_y = \sqrt{{\sigma_s}^2 + {\sigma_\delta}^2} \quad (9)$$

In accordance with the stress and strength "interference" model, the reliability of the aforementioned system can be defined as follows:

$$R = \frac{1}{\sqrt{2\pi}} \int_z^\infty \exp\left(-\frac{z^2}{2}\right) dz \quad (10)$$

$$z = (y - u_y)/\sigma_y \quad (11)$$

The average strength of the wheel in the design is 455 MPa, with a standard deviation of 27.3 MPa. The average stress value from impact analysis is 43 MPa, and the standard deviation of strength is 45.5 MPa. By calculating z=5.92and referencing the reliability table, the reliability R is determined to be 0.999999999984, which is infinitely close to 1.

Reliability analysis of bending fatigue

In the bending fatigue test, the maximum stress value of the analyzed wheel is concentrated on the spokes, and its stress intensity model is as follows:

$$R = P(\delta_n > S_n) = \Phi(z) \quad (12)$$

$$z = -\frac{\delta_n - S_n}{\sqrt{\sigma^2_{\delta_n} + \sigma^2_{S_n}}} \quad (13)$$

The average strength of the wheel in the design is 455 MPa, with a standard deviation of 27.3 MPa , and the standard deviation of strength is 45.5 MPa . The average stress value is 58.786 MPa, and z=5.69. Checking the reliability table, the reliability R is calculated to be 0.999999999936, which is infinitely close to 1.

CONCLUSIONS

Introducing a reliability-based lightweight design approach for wheel development focuses on minimizing wheel mass while maintaining durability and reliability. This methodology involves detailed modeling, mechanical analysis, topology optimization, and subsequent validation through crash and flexural fatigue testing.After the wheels were designed and machined, they were commissioned and tested for durability at the Shanghai Tianma Circuit, completing a total of 150 laps on asphalt with a mileage of 309.45 kilometres. This was followed by over 500 kilometres of daily driving practice and vehicle tuning. Prior to the race, the wheels underwent further tuning at the Formula Dream Circuit in Xiangyang, completing another 150 laps on asphalt and covering a distance of 219 kilometres. Daily driver training and vehicle tuning totalled over 200 kilometres. The commissioning process included straight-line acceleration, braking tests, high-speed obstacle avoidance, and durability tests. Upon completion of the vehicle's commissioning, the spokes and rim were found to be well connected, with no cracks detected in the spokes.After the race, the vehicle was driven an additional 500 kilometres to collect more data and train the driver. The wheels completed a total of 1,388,227 rotations during the testing and race. According to this analysis, the wheels have a minimum service life of at least another 4,000 kilometres, which is sufficient for all race-related tasks. Furthermore, no cracks or fractures were observed on the wheels, the outer surfaces remained intact, and the simulation predictions were validated as accurate.

Combining topology optimization with crash testing and fatigue analysis creates a comprehensive design cycle aimed at optimizing the structural layout, achieving the optimal balance between lightweight construction and performance reliability. Moreover, precise load modeling based on steering and braking conditions allows the design to be specifically tailored to meet the unique demands of racing, setting a new benchmark for efficiency in wheel design.

The reliability-based lightweight design approach can also be applied to other mechanical components where weight and reliability are crucial. Potential applications include aerospace parts, automotive suspension systems, and structural components for electric vehicles — areas where lightweight, reliable components are key to enhancing performance.

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REFERENCES

Ammar, H. R., Samuel, A. M., and Samuel, F. H., "Effect of casting imperfections on the fatigue life of 319-F and A356-T6 Al–Si casting alloys," Materials Science and Engineering: A, Vol.473, No.1-2, pp.65-75 (2008).

Andukuri, S. Y., Pai, A., and Manikandan, M., "Scope of carbon fibre-reinforced polymer wheel rims for formula student racecars: A finite element analytical approach," Journal of The Institution of Engineers (India): Series C, Vol.103, No.4, pp.939-948 (2022).

Balthazar, J. C., and Malcher, L. "A review on the main approaches for determination of the multiaxial high cycle fatigue strength," Mechanics of solids in Brazil, Marcilio Alves & Da Costa Mattos, pp.63-80 (2007).

Burhan, I., Kim, H. S., and Thomas, S., "A refined SN curve model," Proceedings of the International Conference on Sustainable Energy, Environment and Information (SEEIE 2016), Bangkok, Thailand, pp.20-21 (2016).

Celenta, G. , De Simone M. C., "Kinematic and Dynamic Analysis of the Suspension of a Racing Car," International Conference "New Technologies, Development and Applications," Cham: Springer Nature Switzerland pp.513-520(2024).

Deng, X., Zhu, S. P., Wang, L., Luo, C., Fu, S., and Wang, Q. "Probabilistic framework for strain-based fatigue life prediction and uncertainty quantification using interpretable machine learning," International Journal of Fatigue, Vol. 190, pp. 108647 (2024).

Gao, Q., Shan, Y., Wan, X., Feng, Q., and Liu, X., "90-degree impact bench test and simulation analysis of automotive steel wheel," Engineering Failure Analysis, Vol.105, pp.143-155 (2019).

Gardie, E., Paramasivam, V., Dubale, H., Chekol, T., and Selvaraj, S. K., "Numerical analysis of reinforced carbon fiber composite material for lightweight automotive wheel application," Materials Today: Proceedings, Vol.46, pp.7369-7374 (2021).

Gharaibeh, M. A., and Wilde, J. "Research on the creep response of lead-free die attachments in power electronics," International Journal of Structural Integrity, Vol. 15, No. 4, pp. 702–716 (2024).

Gonçalves, M., Monteiro, H., and Iten, M., "Life Cycle Assessment studies on lightweight materials for automotive applications-An overview," Energy Reports, Vol.8, pp.338-345 (2022).

Huang, Z. M. , Kim, H. M. , Youn, J. R. , and Song, Y. S., "Injection molding of carbon fiber composite automotive wheel," Fibers and Polymers, Vol.20, pp.2665-2671 (2019).

Hwang, S. F., Yu, H. L., Liu, Y. J., Chen, Y., and Hsieh, Y. C., "Progressive failure of metal–composite hybrid wheels under impact," Journal of Mechanical Science and Technology, Vol.32, pp.223-229 (2018).

Jiang, X., Lyu, R., and Fukushima, Y., "Lightweight design and analysis of automobile wheel based on bending and radial loads,"IOP Conference Series: Materials Science and Engineering, Vol.372, No.1, IOP Publishing (2018).

Jiang, Y., Le, Q., Zhou, W., Liao, Q., Zhu, Y., and Li,D., "Simulation study on microstructure evolution during the backward extrusion process of magnesium alloy wheel," Materials Today Communications, Vol.35, pp.105480 (2023).

Kaluza, A., Kleemann, S., Fröhlich, T., Herrmann, C., and Vietor, T., "Concurrent design & life cycle engineering in automotive lightweight component development," Procedia Cirp, Vol.66, pp.16-21 (2017).

Liang, Z. Q., Liu, X. T., Zuo, H., and Wang, Y. S., "Design and analysis of suspension system based on tire characteristics,"Journal of the Chinese Society of Mechanical Engineers, Vol.39, No.6, pp.599-608 (2018).

Liu, X. T., Wang, H. J., and Yang, J. F., "Prediction and evaluation of fatigue strength via mechanical behavior of materials," Journal of the Chinese Society of Mechanical Engineers, Vol.43, No.3, pp.229-238 (2022).

Liu, X., Qu, Y., Yang, X., and Shen, Y., "Load spectrum compiling and fatigue life estimation of the automobile wheel hub," Recent Patents on Mechanical Engineering, Vol.14, pp.366-379 (2021).

Liu, X., Yu, X., Tong, J., Wang, X., and Wang, X., "Mixed uncertainty analysis for dynamic reliability of mechanical structures considering residual strength," Reliability Engineering & System Safety, Vol.209, pp.107472 (2021).

Luo, C., Zhu, S. P., Keshtegar, B., Macek, W., Branco, R., and Meng, D. "Active Kriging-based conjugate first-order reliability method for highly efficient structural reliability analysis using resample strategy," Computer Methods in Applied Mechanics and Engineering, Vol. 423, pp. 116863 (2024).

Meng, D., Yang, H., Yang, S., Zhang, Y., De Jesus, A. M. P., Correia, J., Fazeres-Ferradosa, T., Macek, W., Branco, R., and Zhu, S. P. "Kriging-assisted hybrid reliability design and optimization of offshore wind turbine support structure based on a portfolio allocation strategy," Ocean Engineering, Vol. 295, pp. 116842 (2024).

Meng, D., Yang, S., Yang, H., De Jesus, A. M. P., Correia, J., and Zhu, S. P. "Intelligent-inspired framework for fatigue reliability evaluation of offshore wind turbine support structures under hybrid uncertainty," Ocean Engineering, Vol. 307, pp. 118213 (2024).

Mishra, A., Yau, H. T., Kuo, P. H., and Wang, C. C. "Achieving sustainability by identifying the influences of cutting parameters on the carbon emissions of a milling process," The International Journal of Advanced Manufacturing Technology, vol. 129, pp. 1–19 (2024).

Peng, T. J., Kuo, P. H., Huang, W. C., and Wang, C. C. "Nonlinear dynamic analysis and forecasting of symmetric aerostatic cavities bearing systems," International Journal of Bifurcation and Chaos, Vol. 34, No. 4 (2024).

Pinelli, L., Amedei, A., Meli, E., Vanti, F., Romani, B., and Benvenuti, G., "Innovative design, structural optimization, and additive manufacturing of new-generation turbine blades," Journal of Turbomachinery, Vol.144, pp.011006 (2022).

Previati, G., Ballo, F., Gobbi, M., and Mastinu, G., "Radial impact test of aluminium wheels—Numerical simulation and experimental validation," International Journal of Impact Engineering, Vol.126, pp.117-134 (2019).

Raju, P. R., Satyanarayana, B., Ramji, K. , and Babu, K. S., "Evaluation of fatigue life of aluminum alloy wheels under radial loads," Engineering failure analysis, Vol.14, No.5, pp.791-800 (2007).

Raju, S., Vijaya, P. K. A., Kumar, V. S., Manjunath, N., and Nagaraj, H., "Design Optimisation and Life Estimation of Split Hub Geometry of FSAE Car," ASME International Mechanical Engineering Congress and Exposition, Vol.50633, American Society of Mechanical Engineers (2016).

Rasul, A., Karuppanan, S., Perumal, V., Ovinis, M., and Iqbal, M. "An artificial neural network model for determining stress concentration factors for fatigue design of tubular T-joint under compressive loads," International Journal of Structural Integrity, Vol. 15, No. 4, pp. 633–652 (2024).

Saurabh, Y. S. , Kumar, S. , Jain, K. K. , Behera, S. K. , Gandhi, D. , and Raghavendra, S., "Design of suspension system for formula student race car," Procedia Engineering, Vol.144, pp.1138-1149 (2016).

Shinde, T., Jomde, A., Shamkuwar, S., Sollapur, S., Naikwadi, V., and Patil, C., "Failure analysis of a wheel hub of formula student racing car," Journal of The Institution of Engineers (India): Series D, Vol.102, pp.73-78 (2021).

Shinde,Tarang, and Deshmukh, A., "Fatigue analysis of alloy wheel using cornering fatigue test and its weight optimization," Materials Today: Proceedings, Vol.62, pp.1470-1474 (2022).

Sindhwani, Rahul, and Kumar, A., "Design and optimization of suspension for formula Society of Automotive Engineers (FSAE) vehicle," Materials Today: Proceedings, Vol.38, pp.229-233 (2021).

Somayaji, A., Somayaji, S., and Hebbale, A. M., "Studies on modal analysis of aluminium based carbon fibre reinforced optimized alloy wheel used in automotive sectors," Materials Today: Proceedings, Vol.52, pp.274-277 (2022).

Tong, J. C., Liu, X. T., Wang, X. L., Wang, Y. S., and Guo, H., "Lightweight design of the aluminium wheel hub based on reliability," Journal Of The Chinese Society Of Mechanical Engineers, Vol.38, No.1, pp.73-79 (2017).

Wan, X., Liu, X., Shan, Y., Jiang, E., and Yuan, H., "Numerical and experimental investigation on the effect of tire on the 13° impact test of automotive wheel.," Advances in Engineering Software, Vol.133, pp.20-27 (2019).

Wang, C. C., Kuo, P. H., Peng, T. J., Oshima, M., Cuypers, S., and Chen, Y. T. "Voting model prediction of nonlinear behavior for double-circumferential-slot air bearing system," Chaos, Solitons & Fractals, vol. 183, pp. 114908 (2024).

Wang, D., Xu, W., Wang, Y., and Gao, J.,. "Design and optimization of tapered carbon‐fiber‐reinforced polymer rim for carbon/aluminum assembled wheel," Polymer Composites, Vol.42, No.1, pp.253-270 (2021).

Wang, H., Liu, X., Wang, X., and Wang, Y., "Numerical method for estimating fatigue crack initiation size using elastic–plastic fracture mechanics method," Applied Mathematical Modelling, Vol.73, pp.365-377 (2019).

Xiao, D. H., Zhang, H., Liu, X.D., He, T., and Shan, Y.C., "Novel steel wheel design based on multi-objective topology optimization," Journal of Mechanical Science and Technology, Vol.28, pp.1007-1016 (2014).

Xu, W. , and Wang, D., "Fatigue/impact analysis and structure–connection–performance integration multi-objective optimization of a bolted carbon fiber reinforced polymer/aluminum assembled wheel," Composites Part B: Engineering, Vol.243, pp.110103 (2022).

Yang, S., De Jesus, A. M. P., Meng, D., Nie, P., Darabi, R., Azinpour, E., Zhu, S. P., and Wang, Q. "Very high-cycle fatigue behavior of steel in hydrogen environment: State of the art review and challenges," Engineering Failure Analysis, Vol. 166, pp. 108898 (2024)

Yang, S., Meng, D., Wang, H., Chen, Z., and Xu, B. A comparative study for adaptive surrogate-model-based reliability evaluation method of automobile components," International Journal of Structural Integrity, Vol. 14, No. 3, pp. 498–519 (2023).

Zhang, M., Liu, X., Wang, Y., and Wang, X., "Parameter distribution characteristics of material fatigue life using improved bootstrap method," International Journal of Damage Mechanics, Vol.28, No.5, pp.772-793 (2019).

Zhang, M., Song, H., Yan, W., Yue, F., Yang, B., and Chen, S., "Casting and spinning aluminum alloy wheel fatigue properties and life prediction study," Fatigue & Fracture of Engineering Materials & Structures, Vol.46, No.9, pp.3446-3457 (2023).

Zhang, Y., Shan, Y., Liu, X., and He, T., "An integrated multi-objective topology optimization method for automobile wheels made of lightweight materials," Structural and Multidisciplinary Optimization, Vol.64, pp.1585-1605 (2021).

Zhao, X., Gao, P., Zhang, Z., Wang, Q., and Yan, F., "Fatigue characteristics of the extruded AZ80 automotive wheel," International Journal of Fatigue, Vol.132, pp.105393 (2020).

Zhi, S., Liu, H., and Liu, X., "Improved Equivalent Strain Method for Fatigue Life of Automobile Aluminum Alloy," World Electric Vehicle Journal, Vol.15, pp.200 (2024).