STM JOURNALS

International Journal of
Mechanical Dynamics and
Systems Analysis

Volume 2, Issue 2, 2024
July–December
DOI (Journal): 10.37591/IJMDSA

https://journals.stmjournals.com/ijmdsa

Research IJMDSA

A Comprehensive Study of Radial Load Fluctuation on Alloy Wheels for Electric Vehicles

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Abstract

An electric vehicle's alloy wheels are designed to allow for better heat dissipation. Manufacturers carry out many tests of a wheel to be sure that the wheel will fit for safety reasons as also their comfortability level. Therefore, a specific design was selected for which the simulations of alloy wheel were performed under real loading conditions. The main objective of this research is to analyze the effects of radial load fluctuations on alloy wheels in passenger car. Radial loads place high stress on alloy wheels when the vehicle is running and affects their life, so that it has excellent performance. This is important to increase the quality and reliability levels of wheel design, durability standards in automotive engineering. Utilizing advanced fatigue analysis methods, the study shows how different radial loads affect both structural safety and lifetime of alloy wheels for optimizing real-world driving performance. An electric vehicle alloy wheel of Skoda was used for simulation. This study on finite element modeling presents the stress distribution of an alloy wheel. Radial fatigue test implemented using radial experiment suitable for specimen by following industrial standards. Fatigue life cycle of the wheel was measured to achieve material improvement.

Keywords: Electric vehicle, alloy wheels, heat dissipation, simulations, stress distribution, fatigue life

INTRODUCTION

Over the past few years, electric vehicles (EVs) have quickly evolved to a point where they challenge-with promise for better and worse-the dominant engineering conventions of automotive design. This change affects alloy wheels, a critical component. Alloy wheels are important to how the vehicle performs in terms of safety and is an item that contributes significantly towards fuel efficiency. This work presents a comprehensive study of radial load variations on an electric vehicle specific alloy wheel. With developments in EV technology, designs for wheels have had to be more adapted than ever. Contrary to typical vehicles with the internal combustion engines, electric ones operated in another manner show pronounced radial load variations. This might include accelerative forces during propulsion, regenerative braking effects and dynamic weights shifts (or body roll) which all contribute to the rapid small cyclic fluctuations in speed that serve as a unique challenge for alloy wheel durability/performance. This not only is necessary for future design improvements of alloy wheels with higher reliability and longevity but also to improve the fuel efficiency and safety of vehicles. This study evaluates the complex relationship between load dynamics and wheel characteristics, providing key insights that can help inform advancements in automotive design. This research aims to systematically study how radial load variations in the context of electric vehicles, affecting alloy wheels (Figure 1).

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Received Date: November 19, 2024
Accepted Date: November 22, 2024
Published Date: December 06, 2024

Citation: Dinesh Burande, Ravikant Nanwatkar. A Comprehensive Study of Radial Load Fluctuation on Alloy Wheels for Electric Vehicles. International Journal of Mechanical Dynamics and Systems Analysis. 2024; 2(2): 47–56p.

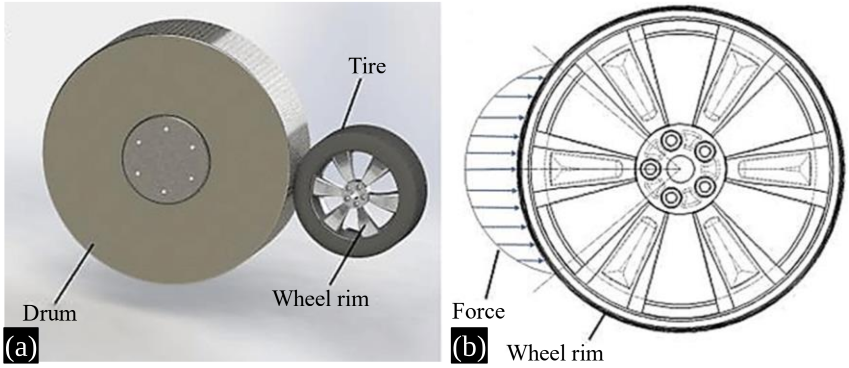


Figure 1. ISO-3006 (a) radial test and (b) uniformly distributed load applied to the wheel rim.

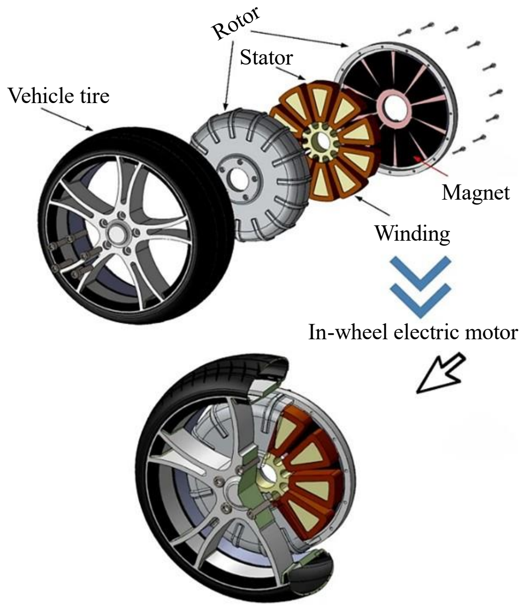


Figure 2. Sensorless based space vector pulse width modulation–direct torque control (SVPWM-DTC) of axial flux permanent magnet synchronous motor (AFPMSM) for electric vehicles.

The goal of the study is to

1. Research radial load oscillations in EVs.
2. Analyze the impact of load fluctuations on structural integrity and fatigue life among alloy wheels.
3. Examine possible changes to the design or solutions for improvements in wheel performance during different load cases.

In this article, a review of these types of wheels dedicated to electric motors will be presented. This includes theoretical analyses, simulations and real-world experimental data collection as well as comparative evaluations of different design approaches (geometries) and materials (Figure 2). The research will cover mostly radial load fluctuations, but thermal management and aerodynamic considerations related aspects may also be touched wherever required in terms of the wheel performance.

LITERATURE SURVEY

Ghosh et al. [1] deal with influence of alloying content on dynamic properties accompanied by wheel composition, such as fatigue resistance and implementation for the purpose of weight reduction.

Investigated with different manufacturing processes and how they affect wheel durability, as well in performance at different loads. Kim and Lee [2] studied high-torque electric motors: from load variations to the fatigue life of alloy wheels. Zhang and Kawasaki [3] utilized finite element analysis (FEA) for optimized wheel design by achieving uniform load distribution along with extended service life. EV performance testing Evaluated the impact of wheel material and design on an EV's range, handling characteristics. Nanomaterials were another area of potential which was identified by Choi and Park investigated the role that this new field could play for improving certain aspects, such as working with non-cutting tool materials to achieve light weighting and strength in alloy wheels [4]. Smith et al. reported on better thermal performance, weight savings [5]. They investigated advantages of aluminum-magnesium alloys for EV wheels. Brown and Harris reported on how alloy wheel design can influence the aesthetics of an EV and consumer acceptance to market, focusing on new emission-free designs are wanted by auto-designer that lightweight with unique look doper ganger wheels suitable for a hypermilling acceleration experience [6]. Zhao et al [7] discuss the advantages and limitations of using magnesium alloys within an electric vehicle by exploring corrosion resistance, as well as cost. Hybrid manufacturing techniques and their cost-effectiveness as well as performance advantage study by Lee and Park for alloy wheels [8]. Wang et al. [9] investigated EV load variation characteristics, demonstrating their impact on radial loads by regenerative braking and motor torque. FEA-based simulation approach for the study of wheel subjected by dynamic load along with possible design modifications during development cycle to achieve desired durability. Evans and Johnson [10] discussed assessment of alloy wheels on a fleet of EVs showing improvements in handling and reductions to energy consumption. Nguyen et al. [11] examined the cost-performance tradeoffs in producing alloy wheels, advocating for a low-cost remedy. The commercial feasibility of nanomaterials and smart sensors to be utilized in alloy wheels such as enhancements in strength along with allowing load monitoring were established [12].

DESIGN AND EXPERIMENTATION

The analysis of the working condition of wheel shows that, they are subjected to two major loads, that is, direct load (radial load because of gravity) and tangential/axial load (due acceleration torque or braking torque) (Table 1) [13]. The wheels of an EV need to satisfy bending and radial endurance test conditions as per industrial automobile standards (Table 2).

Procedure for Bending Test

The bending moment can be calculated as,

$M = ((\mu * R) + d) * F * S (1)$

Table 1. Material properties

Material properties	Aluminum A356.2	Aluminum 7075-T6
Ultimate tensile strength (S_{ut})	250 MPa	570 MPa
Tensile yield strength (S_{yt})	230 MPa	503 MPa
Modulus of elasticity (E)	72.4 GPa	71.7 GPa
Poisson's ratio	0.33	0.33
Density (ρ)	2810 kg/ m^3	2700 kg/m^3

Table 2. Loading coefficient specified according to the standards.

Division of wheel	Light alloy wheel	
	Coefficient	*Number of revolutions*
Wheels under 100 mm in offset	1.8	10^3
	1.5	10^5
	1.35	25×10^3
	1.33	10^3
	1.26	10^3
	1.1	10^3

According to the Japanese Industrial Standards (JID D 4103) $\mu = 0.7$

$d = 37$ mm = 0.037m, $F = 4414.5$ N

Bending moment $M = ((\mu * R) + d) * F * S$

$= ((0.7*0.1904) + 0.037) * 4414.5*1.5$

$M = 1589$ N-m.

Procedure for Radial Test

The radial load (F) can be calculated as,

$F = P \times C$

where, P = thrust force, C = dynamic load capacity of the wheel.

Angular velocity can be calculated using,

$$= \omega = \frac{v}{r} = \frac{22.22 \text{ m/s}}{0.1904} = 116.70 \text{ rad/sec}$$

Tensile Stress Calculation in Rim

Considering 5 spokes for alloy wheels,

$2\alpha = 2\pi/5$

$\alpha = 0.628$ radians = 35.98˚

Calculation of rim mass (m)

Radius of rim = 175 mm

$$(m) = \frac{(2800 \times 166 \times 36)}{1000 \times 1000} = 0.016 \text{ kg/m}$$

Tensile stress calculations

Applying S Timoshenko's equations,

$f(a) = 0.7992$, $f(\alpha) = 0.00302$ and $\sigma = 1.371$ N/mm^2

Computer-Aided Design Modeling (Figures 3–5)

Initial input parameters,

1. Radial force on wheel = 9.93 kN
2. Pressure on rim surface = 0.303 N/mm^2
3. Angular velocity of rim = 116.7 rad/s.

Figure 3. Alloy wheel: computer-aided design (CAD) model.

Figure 4. Alloy wheel: mesh model.

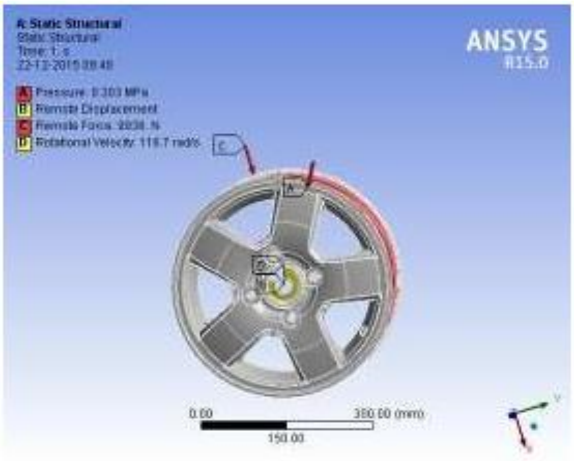


Figure 5. Input parameters and constraints.

Experimental Analysis

Figure 6 shows a typical standard test setup of radial fatigue test with driven rotatable drum (Table 3 and Figure 7) [14]. The drum axis runs parallel to the test wheel axis and features a smooth surface that is broader than the section width of the loaded test tire [4], which include the loading normal to the surface of drum and in line radially with center of test wheel, as same type of force applied statically or dynamical. The test wheel is attached to the hub using nuts that are tightened to the torque specifications provided by the vehicle or wheel manufacturer [5]. This is how the total weight of car gets balanced through a vertical reaction force coming from road via the tire. This load continuously applies radial pressure to the wheel when the car is moving (while travelling it turns into a cyclic lateral burden) [6]. As a key design objective for ensuring structural integrity, evaluating the fatigue strength of wheels under radial load is essential [8].

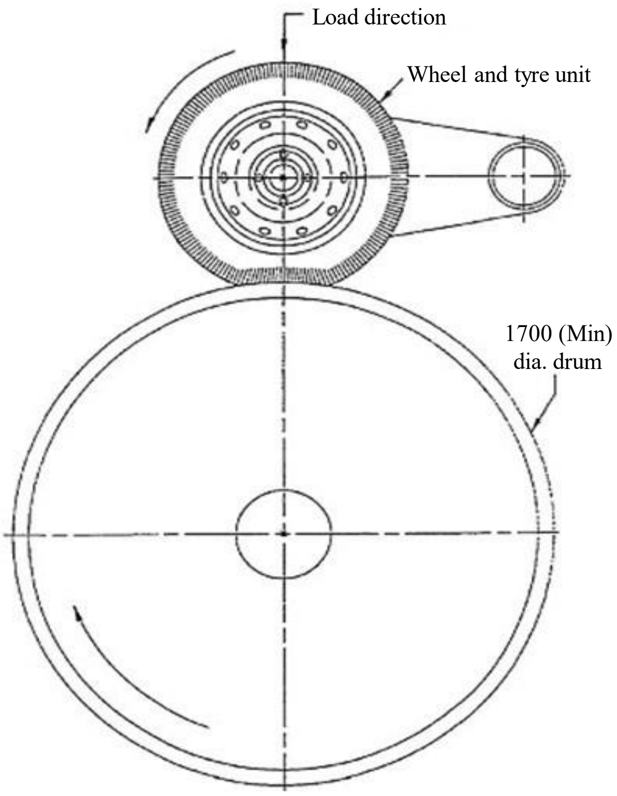
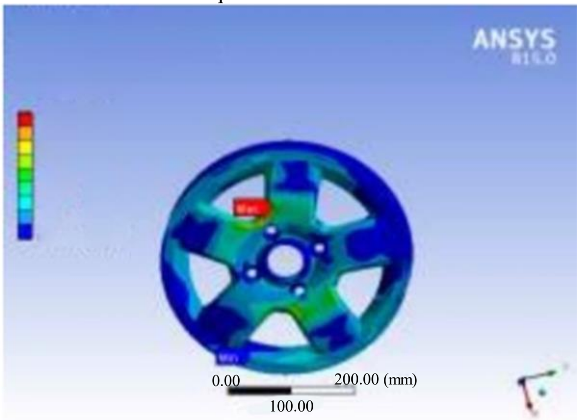


Figure 6. Radial fatigue test set up.

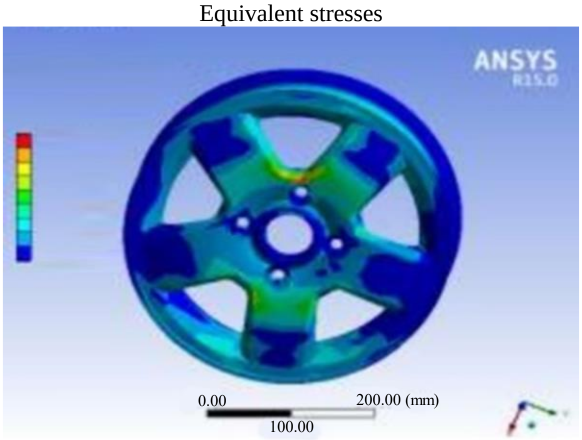
A356.2

Equivalent stresses

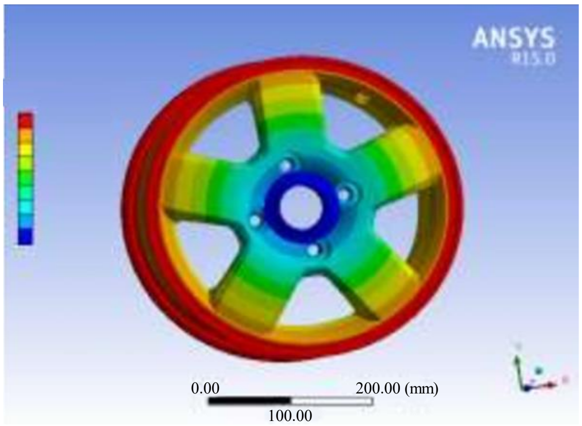


7075-T6

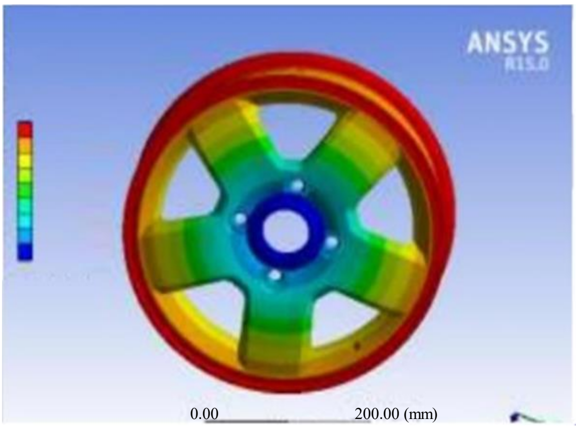
Equivalent stresses



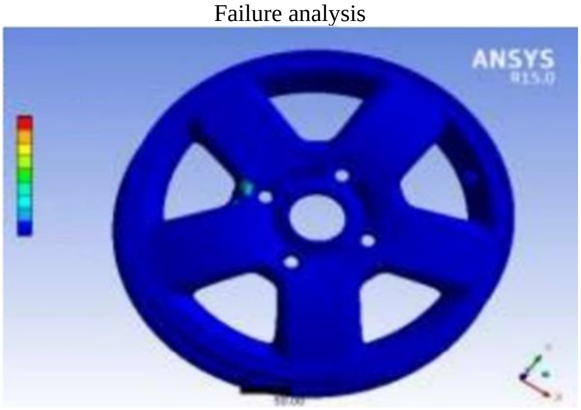
wheel rim deformation



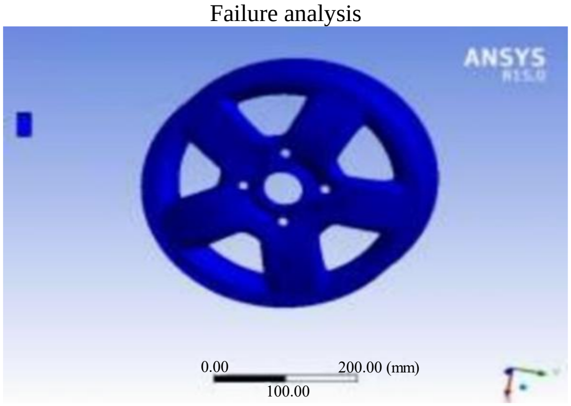
wheel rim deformation



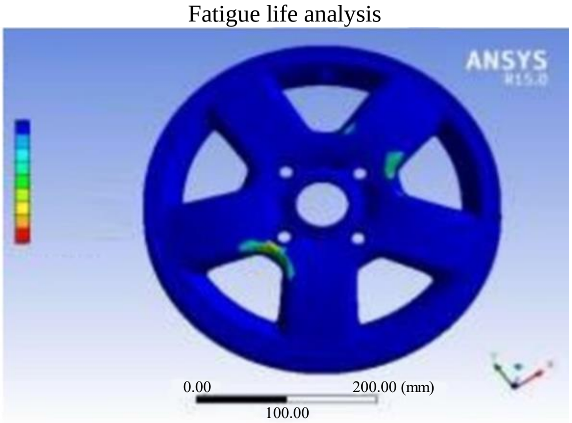
Failure analysis



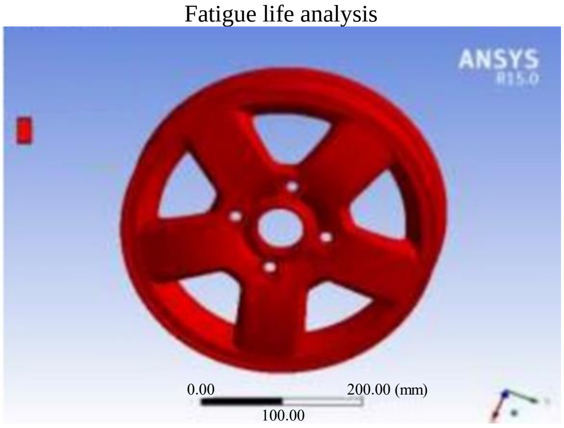
Failure analysis



Fatigue life analysis



Fatigue life analysis



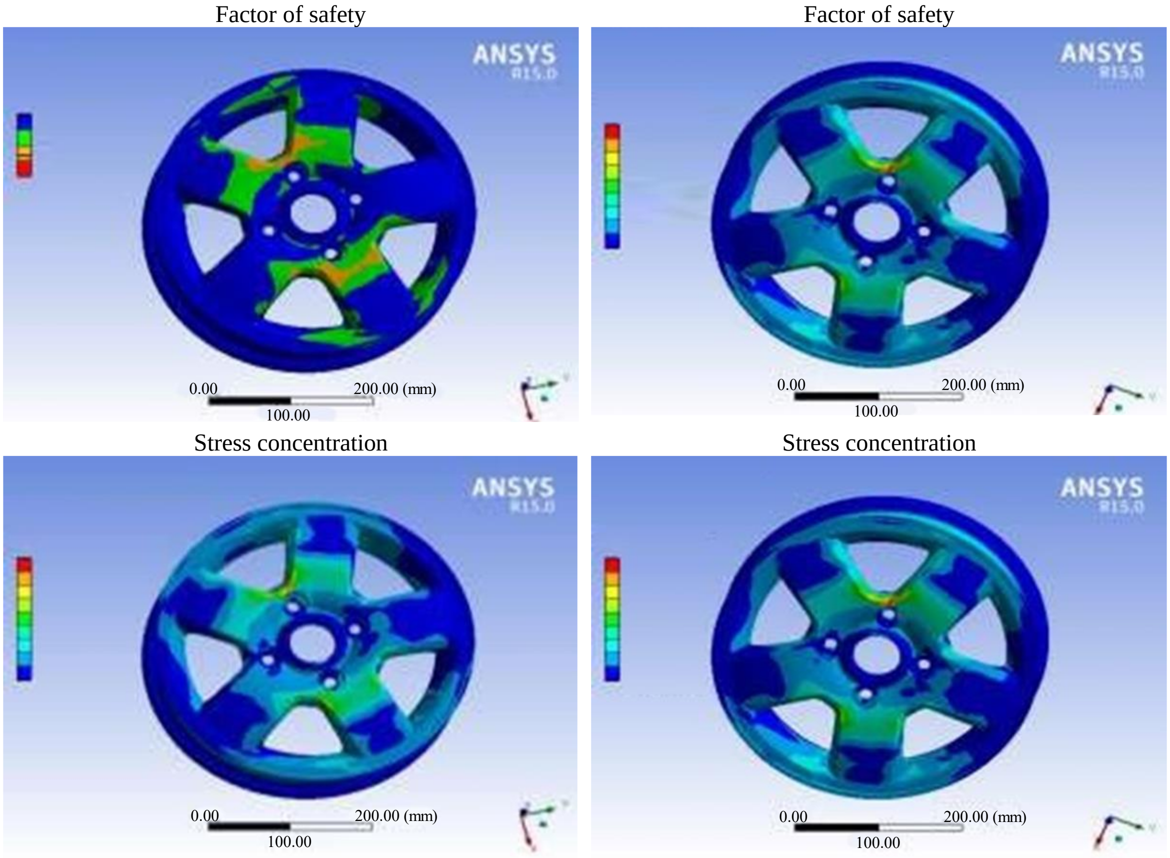


Figure 7. Simulation results comparison of aluminum alloy wheels for 7075-T6 versus A356.2.

Table 3. Cyclic stresses.

Cycles	Alternating stresses (MPa)	Alternating stresses (MPa)
10	468.01	1067.08
20	419.16	955.70
50	362.32	826.00
100	324.50	739.87
200	290.63	662.64
2000	201.51	459.45
10000	156.00	355.69
20000	139.72	318.56
100000	108.16	246.62
200000	96.87	220.88
1000000	75	171.00

Test Condition

Calculation of radial load (Fr) = F. K
where,
According to JIS-D 4202,
Maximum load applied on wheel (F) = 105

Test Termination

The test shall be conducted in any of the following two cases:

1. The wheel is not able to carry the load
2. Pre-test crack propagating or visible stress-induced cracking that goes through a portion of the wheel section itself.

Figure 8. Radial fatigue testing machine setup.

Table 4. Accelerated test factor.

Division of wheel	**Light alloy wheel**	
	Coefficient K	***Specified number of revolutions 10^4***
Wheels 17.5 or under in nominal rim diameter	2.25	50×10^3
	2.2	10^3
	2.0	10^3
	1.8	10^3
	1.4	10^3

Table 5. Experimental fatigue test results.

Radial fatigue test	
Test load / weight (N)	9930.4
Nut torque (initial)	110 N-m
Test cycles	8.5×10^5
Dynamic pressure test (DPT) result	Crack initiation from 8.15 lakh cycles

Radial Fatigue Testing Machine

Figure 8 shows the radial fatigue testing machine. This is crucial factor for vehicle safety and durability of the wheel (Tables 4 and 5). In this respect, the issue of strength and fatigue life cycles in a wheel is to be considered [15–17]. The radial load fatigue test is done. For radial fatigue testing machine, please refer to Figure 8. Fix the bolt to assemble the alloy wheel. Once the machine is initialized with an initial radial load of 3.998 kN (as per the hydraulic press) [18], the driver drum is set to a speed of 80 km/h, enabling the rotation of the alloy wheel [19, 20]. The machine is stopped after minimum five lakh cycles and checked for crack and then the process was started back again [21–24].

As per JIS-D-4103 (radial test) initial parameters,
Radial force = 9932 N
Number of cycles = 850000
Size of wheel = 14 inches

Considering "J" shaped flag with rim width as 7 inches, offset as 37 mm and weight in a range of 9.8 to 10 kg.

RESULTS AND DISCUSSION

The radial fatigue life cycle of alloy wheel was determined. It was compared also for Aluminum A356. Aluminum 7075-T6 material is used for making alloy wheel. The use of steel as the existing component is replaced with an alternate lightweight aluminum alloy having almost same properties but

Table 6. Results for radial fatigue test.

Parameters	Aluminum A356.2	Aluminum 7075-T6
Von Mises stresses	43.95 MPa	35.75MPa
Displacement	32.33mm	23.81mm
Factor of safety	2.1528	3.085
Life of alloy wheel	7.995×10^5	1×10^6

Table 7. Comparative results of alloy wheels.

Material A 356.2	Fatigue life cycle
Simulation results	Radial fatigue life 7.995×10^5 cycles
Experimental results	Experimental found 8.15×10^5 cycles

20% less density. The maximum equivalent stress (Von Mises stress) is experienced in Aluminum A356. The maximum stress on 2 alloy wheel is observed as 43.95 MPa and the minimum was about with a value of approximately 0.008 MPa but for Aluminum 7075-T6 equivalent stress (Von Mises stress) developed are 35.75 MPa and minimum were 0.024 Mpa. The alloy wheel must comply with the Automotive Industry Standard (AIS) 073 (P1 and P2), which specifies a maximum radial load of 75 kN. Additionally, the wheel size must range between 12 and 24 inches. According to AIS 073 (P1 and P2), the rim should withstand a minimum required number of life cycles under the specified radial load. Wheels, as per IS 9436, shall pass the required tests (Tables 6 and 7).

CONCLUSION

- The stress developed in 7075-T6 is less as compared to Aluminum A356.2 alloy wheel.
- The maximum stress experienced by the Aluminum A356.2 alloy wheel was 43.95 MPa, while for the aluminum 7075-T6 alloy wheel, it was 35.5 MPa.
- It is observed clearly that the safety factor was good in Aluminum 7075-T6 compared to Aluminum A356.2 alloy wheel.
- Fatigue life was not eternally feasible; fatigue life of alloy wheel of Aluminum A356.2 is 7.9985×10^5 cycles and of Aluminum 7075-T6 Alloy wheel is 1×10^6 cycles.
- Aluminum 7075-T6 grade is best suitable to form alloy wheels as it is of constructive relevance.

Conflicts of Interest

The authors attest that the publication of this work is without conflicts of interest.

Funding Statement

No fund was obtained for research or publication of this paper.

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