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Design, Simulation andAnalysis of Self-Adjusting Bicycle Front Wheel

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Abstract:*The primary requirement of front suspension in bicycles is to absorb shocks, provide better handling, riding comfort and safety to the rider. A newly designed front wheel with five self-adjusting spokes that have provision of shock absorption directly through the standard bicycle rim can be an inclusion to the effectiveness in the design of the conventional bicycle rim with front shock absorbers and to overcome the limitations offered by a prototype of four spoke self-adjusting wheel design. The newly designed bicycle wheel is based on the standard bicycle rim with an arrangement of five Spring Steel Strips instead of conventional spokes. A Pentagonal Hub is used that supports the Axle of the bicycle and Spring Steel Strips. The Spring Steel Strips act as supporting member as well as a damping member. The wheel is modelled using Siemens NX 11.0. The Finite element analysis (FEA) of the newly designed wheel is carried out using NX NASTRAN. For the analysis purpose, different loading conditions on the bicycle wheels are considered. The results of analysis are obtained in the form of stress generated in the bicycle rim and spring steel strips and are compared with the Safe Design Stress Parameters to ensure the Safety of Design.*

Keywords: *Standard Bicycle Rim, Bicycle Wheel,Shock, Shock Absorption, Spring Steel Strips, Pentagonal Hub, Finite Element Analysis*

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I. INTRODUCTION

The front wheel of the bicycle is the member that is first subjected to the shocks and loads and then to the other parts of the bicycle. Several different types of standard wheels such as spoked wheels, disc type wheels are conventionally used, in these standard wheels there are no provisions for shock absorption, this results in exhaustion to rider during riding. A prototype of wheel having four self-adjusting spokes made of spring steel with a square hub was constructed as shown in Fig. 1.

Fig. 1 Self-adjusting four spoke prototype

The four self-adjusting spokes had some major limitations as follows:

- Elliptical shape of bicycle rim.
- Less number of supporting spokes.
- Eccentric displacement of square hub will turning.

The main reason for the newly designed wheel on standard available rim with five self-adjusting spokes made up of spring steel is to overcome the above limitations and absorb shocks directly through the wheel itself resulting into efficient shock absorption and smooth and trouble-free riding.

II. DESIGN

The design of front wheel is simple and sturdy in construction and has an additional feature of shock absorption. Standard rim available in market is adopted to ensure Standardization. Design of the front wheel consist of Spring Steel Strips, a Steel Pentagonal Hub, and Conventional Bicycle Rim. The wheel design is based on the principle of self-adjustment and damping capacity of the spring steel strips. The new design of wheel consists of Axle, Pentagonal Hub, Spring Steel Strips, Standard Bicycle Rim, and Tubeless Rubber Tire and the connection of the components is as shown in Fig. 2. There are two fixed points for connection for the

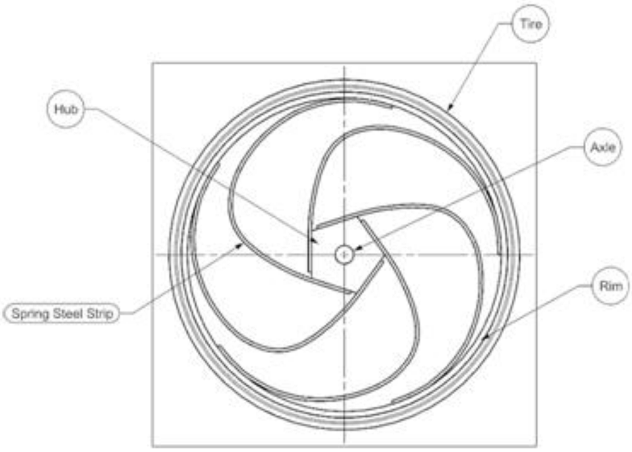

Fig. 2 Different components of the wheel

spring steel strips and they actlike a damping member when loads and shocks are experienced during motion of the bicycle.The strips get elastic deformation with the application of load and shocks during motion. This elastic deformation of strips produces damping effect that results in absorption of shock directly through the wheel. Thus, provision ofbetter shock absorption.

III. SIMULATION

The simulation of the bicycle wheel is carried out in Siemens NX 11.0. The FEA is basically divided into three parts PRE, SOLVER, and POST. The Finite Element Analysis is an effective computational method to obtain deformation results for the front wheel. The PRE process part includes the creation of the model, preparation of geometry of mesh, allocation of material to different components. The meshing of the wheel is conducted by 3D

Fig. 3 Automatic Meshing generated by the Software

Tetrahedral Mesh. The mesh size is optimized automatically by the software. The generated meshing of the wheel is as shown in Fig. 3. The components are connected with each other through mesh mating – glue coincident type.
Materials allocated to different components are as follows:
Axle – Steel
Pentagonal Hub – Steel
Strips – Spring Steel (AISI Steel 1008 HR)
Tire – Rubber (poly-urethane-soft)
The NX NASTRAN Solver uses Finite Element Method (FEM) and Element Iterative Solver is employed. Structural type of analysis is conducted for the solution of the wheel. Linear Statics – Global Constraints solution type is employed for the solution of the load conditions on the wheel.

IV. THEORY FOR ANALYSIS

The FEA is conducted in Siemens NX. Finite ElementAnalysis of newly designed wheel is carried out by considering the following effects:

- Effect of Total Combined Weight (Rider and Bicycle)
- Effect of Driving Torque
- Effect of Braking Torque
- Effect of Driving Torque and Total Combined Weight (Dynamic Driving Loads)
- Effect of Braking Torque and Total Combined Weight (Dynamic Braking Loads)

Different mass of the rider, mass of bicycle as well as total combined mass are assumed and are shown in TABLE 1.

Table 1 Total Weight (Rider + Bicycle)

Massof Rider (m) [Kg]	Mass of Bicycle (M_b) [Kg]	Total Combined Mass (M) [Kg]
70	15	85
85	15	100
100	15	115

As the bicycle is in motion, the spring steel strips are the members that constantly deflect due to shocks and loads. So, failure may occur at spring steel strips. Thus, assuming Factor of Safety for spring steel as 2 ($F_s = 2$) [2].Spring Steel

S_{ut}= 340 N/mm^2[5]S_{yt} = 285 N/mm^2[5]

For Stationary Condition (i.e. Rider on the bicycle and no motion of bicycle), the designing is done considering S_{yt}. Therefore, Safe Design Stress for the stationary condition is 142.5 N/mm^2.
For Dynamic Condition (i.e. Rider on the bicycle and bicycle in motion), the designing is done considering S_{ut}. Therefore, Safe Design Stress for the dynamic condition is 170 N/mm^2.
For analysis, the Elemental Nodal Stress generated should be less than the Safe Design Stress.

4.1 Effect of Total Combined Weight

Assuming cycle is in the stationary condition and the loads acting on the wheels of the bicycle are due to Rider's weight as well as Bicycle's weight. Also assuming the weight of the bicycle as 15 kg and the masses of the rider as stated above in TABLE 1. The masses of the rider as well as mass of the bicycle are summed up and then the combined mass (M) is converted into weight through given (1) below:

$$W = M * g \qquad (1)$$

The Total combined mass is converted to Total combined weight (W) as show in TABLE 2. The Normal Reaction Force that act on the wheels of the bicycle is due to the Total Combined Weight as shown in the (2). The Normal Reaction Forces produced act in the vertically upward direction as shown in Fig. 4.

$$W=N \qquad (2)$$

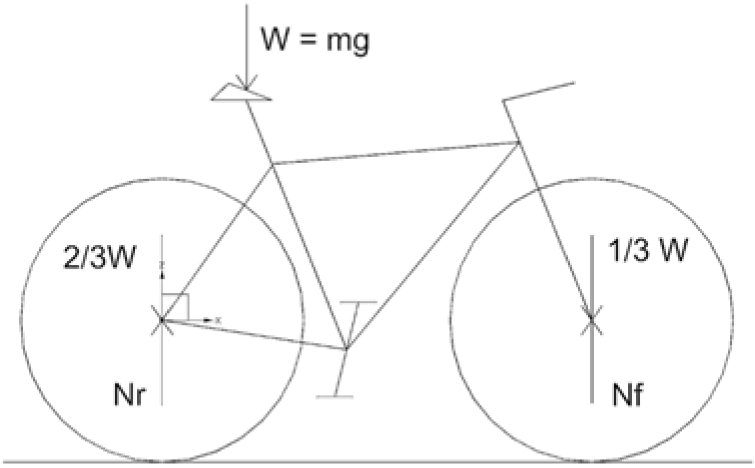

Fig. 4 Loads on Stationary Bicycle

From the Center of Gravity, the Total Combined Weight acting on the wheels get distributed. On the rear wheel, the Total Combined Weight acting is 2/3 times and on the front wheel is 1/3 times of Total Combined Weight (W) as shown in Fig. 3. After conducting the analysis in NX Design, the Elemental nodal stress obtained is as shown in TABLE 2.

Table 2 Nodal Stresses on Front Wheel

Total Combined Weight (W) [N]	Total Combined Weight on Front Wheel (W_f) [N]	Nodal Stress in front wheel [N/mm^2]
833.85	277.95	52.01
981	327	64.05
1128.15	376.05	70.37

Elemental Nodal Stresses generated in the front wheel due to the combined weight on front wheel (Wf) is less than the Safe Design Stress for Static Loads i.e. 142.5 N/mm2. Thus the Design is Safe.

4.2 Effect of Driving Torque

Assuming the bicycle is moving with constant velocity on a road, then the pedal force on the rear wheel should be more than the resisting force that is opposing the bicycle motion. These resistant forces opposing the bicycle motion are Gravity,Aerodynamic Drag, Rolling Resistance and Internal Bicycle Friction. Here Total Combined Mass (M) and zero Inclination (Ø = 0º) is taken into consideration for Calculations.

The Driving/Pedaling force produced by the rider through pedaling is obtained by the given (3):

F = Mg* SinØ + Crr*Mg + 0.5 Cd ρAv2[1](3)

This above equation is taken into consideration when Angle of Inclination (Ø) is to be considered. So for no inclination (4) is considered to find pedaling force.

F = Crr*Mg + 0.5 Cd ρAv2[1](4)

Crr, Cd and Cd * A (Effective Frontal Area) is based on different factors[3] such as road condition, type of bicycle, rider’s body position and values as shown in TABLE 3.

Table 3 Values of Crr, Cd and Cd * A

	Values
C_{rr}	0.005
C_d	0.85
$C_d * A$	0.6

The pedaling torque produced at the wheels can be determined from the given (5). The values of pedaling torque that produces stress in the wheel as shown in TABLE 4.

$T = F * R$ (5)

Table 4 Pedaling Torque

Total Combined Mass (M)[Kg]	Pedaling Torque (T)[Nm]
85	4.46
100	4.68
115	4.9

The values of Elemental Nodal Stress generated due to Pedaling Torque is as shown in Fig. 5. ElementalNodal Stress generated in the wheel due to pedaling is less than the Safe Design Stress i.e. 170 N/mm^2. Thus, the design is safe when pedaling torque acts on the wheel.ElementalNodal Stress generated in the wheel due to pedaling is less than the Safe Design Stress i.e. 170 N/mm^2. Thus, the design is safe when pedaling torque acts on the wheel.

4.2 Effect of Braking Torque

The braking torque is the torque produced at the wheels while braking. The effect of the braking torque is higher than the effect of the pedaling torque. So it is necessary to consider Effect of Braking Torque for safe design of the wheel. Here, Total combined mass (M) is taken into consideration for calculations.
The braking torque (Tb) can be determined by the following (6):

$E = T_b * \theta$[4](6)

It is assumed that the bicycle is in motion at a constant velocity of 5.56 m/s (20 km/h). Assuming 8 seconds as the time taken by the bicycle to stop. For calculation of braking torque, the total energy of the wheel is calculated as follows:

E = Kinetic Energy (K.E.) + Energy of rotating body
$= 0.5mv^2 + 0.5I\omega^2$ [4]

Moment of Inertia (I) = $M_b * R$[4]

Angular velocity of wheel (ω) = V/R = 19.04 rad/s

Now, consider the kinematic equations of motion of linear form and converting them to polar form to determine the angular acceleration of wheel (α)as shown in TABLE 5.

Table 5 Kinematic Equations

Linear Form	Polar Form
$v = u + at$	$\omega = \omega_0 + \alpha t$
$s = ut + 0.5 at^2$	$\theta = \omega_0 t + 0.5\alpha t^2$
$v^2 = u^2 + 2as$	$\omega^2 = \omega_0^2 + 2\alpha\theta$

Angular Acceleration (α) = $\omega / t = 2.38$ rad/s^2
The angular distance (θ) traveled by the wheel during braking is given by solving the polar form of kinematic (7):

$\theta = \omega_0 t + 0.5\alpha t^2$[4](7)
$\theta = 76.16$ radians

The Braking Torque on the wheel can be determined by the following (8) and its values is as shown in TABLE 6.

$T_b = E / \theta$(8)

Table 6 Braking Torque

Total Combined Mass (M)[Kg]	Braking Torque (T)[Nm]
85	20.29
100	23.34
115	26.38

Elemental Nodal Stress is taken into consideration to know whether the stress generated in the elements due to braking torque are under the Safe Design Stress Limit. The values of Elemental Nodal Stress due to Braking Torque is shown in Fig. 5.

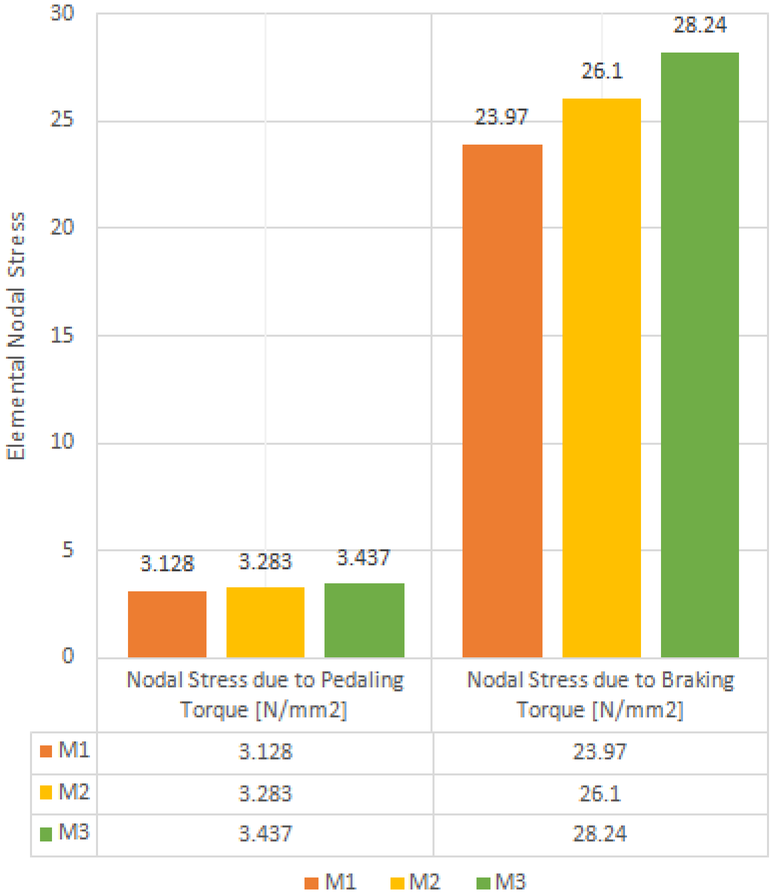

Figure 5 Elemental Nodal Stress due to Driving and Braking Torque

Elemental Nodal Stress generated in the wheel due to braking is less than the Safe Design Stress i.e. 170 N/mm^2. Thus, the design is safe when braking torque acts on the wheel.

4.3 Effect of Driving Torque and Total Combined Weight

For the dynamic analysis of the wheel, the *Effect of Driving Torque and Total Combined Weight*is considered. Considering the theory of *Effect of Driving Torque*, the Driving/Pedaling force produced by the rider through pedaling is obtained by the (4) also considering the resisting forces on bicycle and rider.
Power produced by the *rider of different weight* by pedaling can be given by the (9) given below:

$$P = F*V \tag{9}$$

The power obtained on the wheel is always less than the power obtained by pedaling because of the drivetrain losses which are assumed to be *3% of the Pedal Power*. Total power available on the wheel can be given by the (10) below:

$$P_w = (1-0.03) *P \tag{10}$$

The pedaling torqueproduced on the wheels is given by (11) and its values for different combined mass is as shown in TABLE 7. The RPM of the wheel for a constant velocity of 5.56 m/s can be given by (12):

$$P_w = 2\pi NT / 60$$
$$T_w = P_w*60 / 2\pi N \tag{11}$$
$$V = \pi DN / 60$$
$$N = V * 60 / \pi D (12)$$

Table 7: Power and Torque on wheel

Combined Mass (M) [kg]	Power on wheels (P_w) [Watts]	Torque on the wheels (T_w) [Nm]
85	82.51	4.52
100	86.51	4.74
115	90.44	4.95

Considering the theory of Effect of Total Combined Weight, the mass of the rider as well as the mass of the bicycle are summed up and then the combined mass (M) is converted into combined weight (W) through equation (1). The combined weight acting on the front wheel (Wf) is 1/3 times of the Total Combined Weight (W).For the Dynamic Analysis of the front wheel, both the Pedaling Torque (T) on the wheel as well as Combined Weight on Front Wheel (Wf) are considered to be acting simultaneously. The Elemental nodal stress generated due to Driving Torque (T) and Combined Weight on Front Wheel (Wf) loads is less than the Safe Design Stress for Dynamic Loads i.e. 170 N/mm2. Nodal Stresses generated in the wheel is shown in Fig. 6.

4.4 Effect of Braking Torque and Total Combined Weight

For the dynamic analysis of the wheel, the Effect of Braking Torque and Total Combined Weight are considered. Considering the theory of Effect of Braking Torque, the effect of the braking torque is higher than the effect of the pedaling torque. The values of the Braking Torque produced can be determined by (8) and its values are shown in TABLE 6.Considering the theory of Effect of Total Combined Weight, the mass of the rider as well as the mass of the bicycle are summed up and then the combined mass (M) is converted into combined weight (W) through (1). The combined weight acting on the front wheel (W_f) is 1/3 times of the Total Combined Weight (W).For the Dynamic Analysis of the Wheel, both the Braking Torque (T_b) as well as Combined Weight on the front wheel (W_f) are considered to be acting simultaneously.

The Elemental nodal stress generated due to Braking Torque (T_b) and Combined Weight on Front Wheel (W_f) is less than the Safe Design Stress for Dynamic Loads i.e. 170 N/mm^2. Thus, the design is safe for braking. Elemental Nodal Stresses generated in the wheel is shown in Fig. 6.

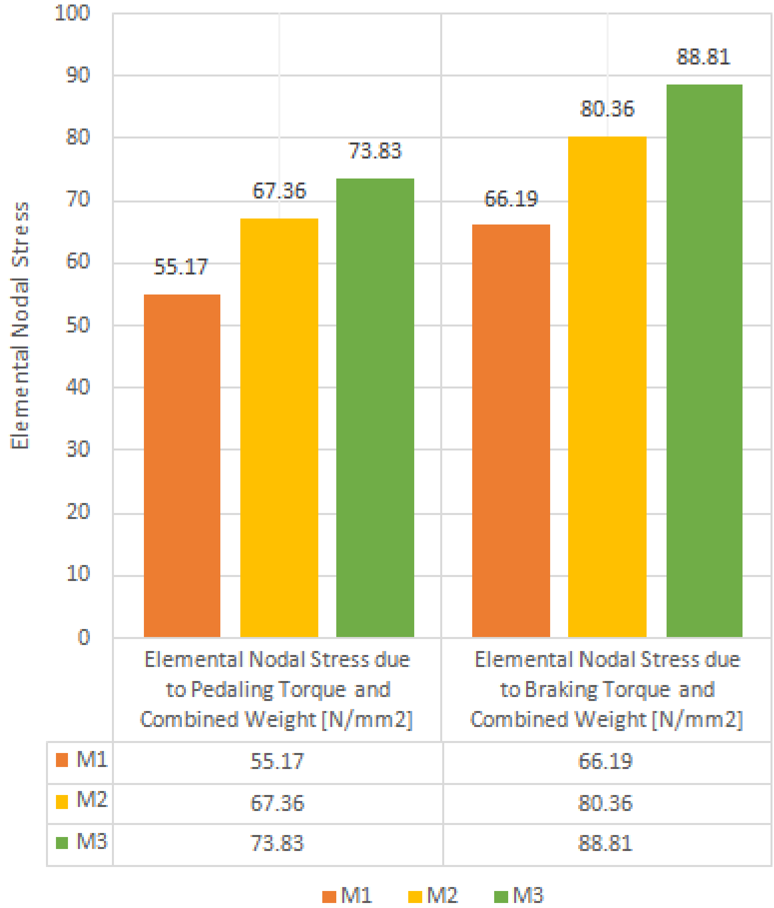

Figure 6: elemental Nodal Stress for Dynamic Loading

V. CONCLUSION

- With the help of NX Design Simulation tool, Finite Element Analysis is conducted and elemental nodal stress are obtained for different types of loading conditions by considering above stated effects for different weight of riders. These stress values obtained is compared with the Safe Design Stress.
- After computation of the theory of analysis in Simulation tool of Siemens NX on the wheel, the FEM result show that the failure of the wheel will occurs at the strips if the Elemental nodal stress exceeds the Safe Stress Limit.
- In all the above theories, the Elemental nodal stress is not exceeding the Safe Design Stress Limit. Therefore, the wheel design is safe for the above stated effects.
- This wheel can be beneficial for several applications such as wheelchairs, normal low-cost bicycles, mountain bicycles, etc.

The scaled deformation of the wheel for maximum assumed mass of rider of 100 kg and mass of bicycle of 15 kg by considering the above theories of analysis. This concludes that the design of the wheel is safe from failure for maximum mass of rider.

1. Effect of Combined mass is as shown in Fig. 7. The maximum nodal stress generated i.e. 3.437 N/mm^2 is under Safe design stress limit for stationary loading conditions of 142.5 N/mm^2.

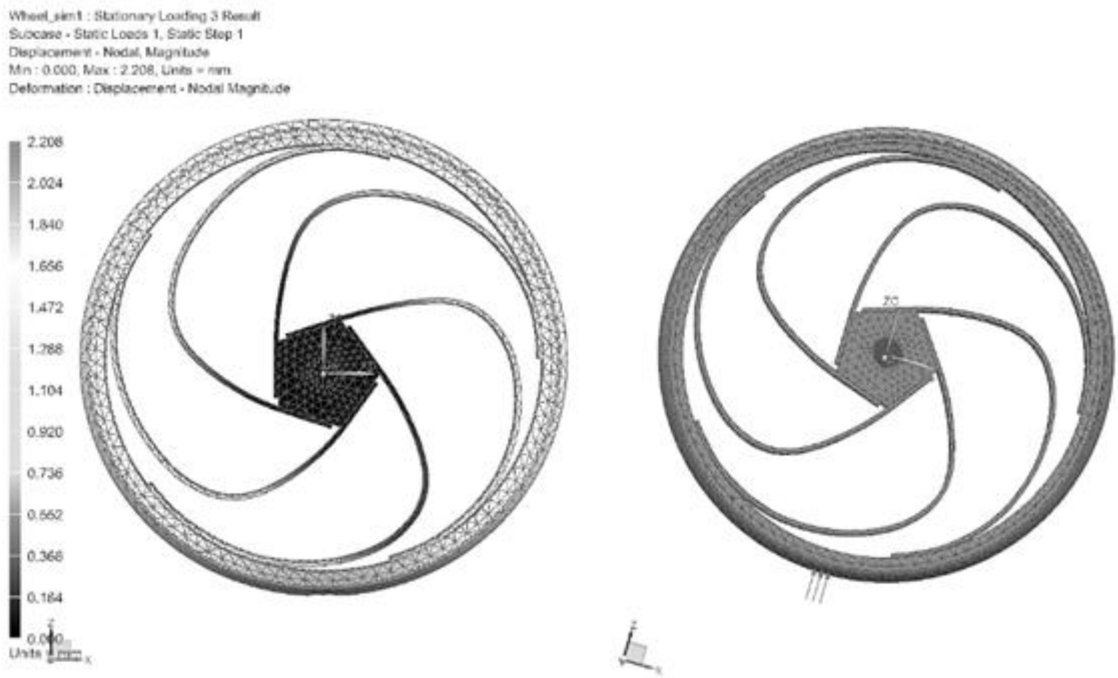

Figure 7: Scaled deformation of effect of combined weight (Rider + Bicycle)

2. Effect of Driving Torque is as shown in Figure 8. The maximum nodal stress generated i.e. 3.437 N/mm^2 is under Safe design stress limit for dynamic loading conditions of 170 N/mm^2.

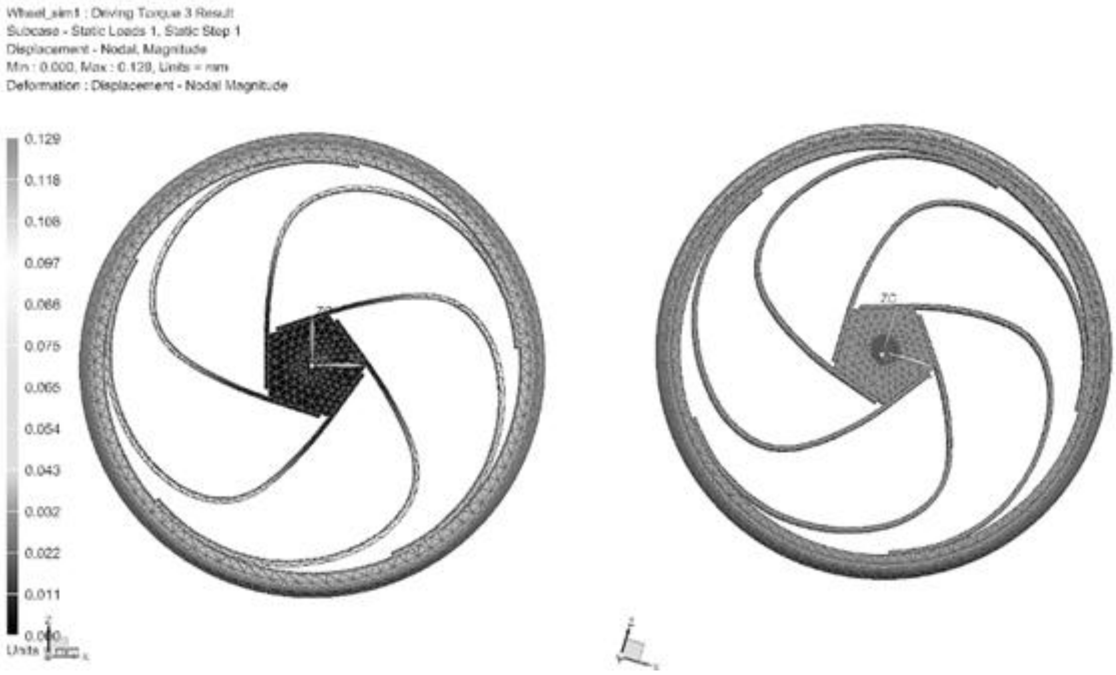

Figure 8 Scaled deformation of effect of driving torque

3. Effect of Braking Torque is as shown in Figure 9. The maximum nodal stress generated i.e. 28.24 N/mm^2 is under Safe design stress limit for dynamic loading conditions of 170 N/mm^2.

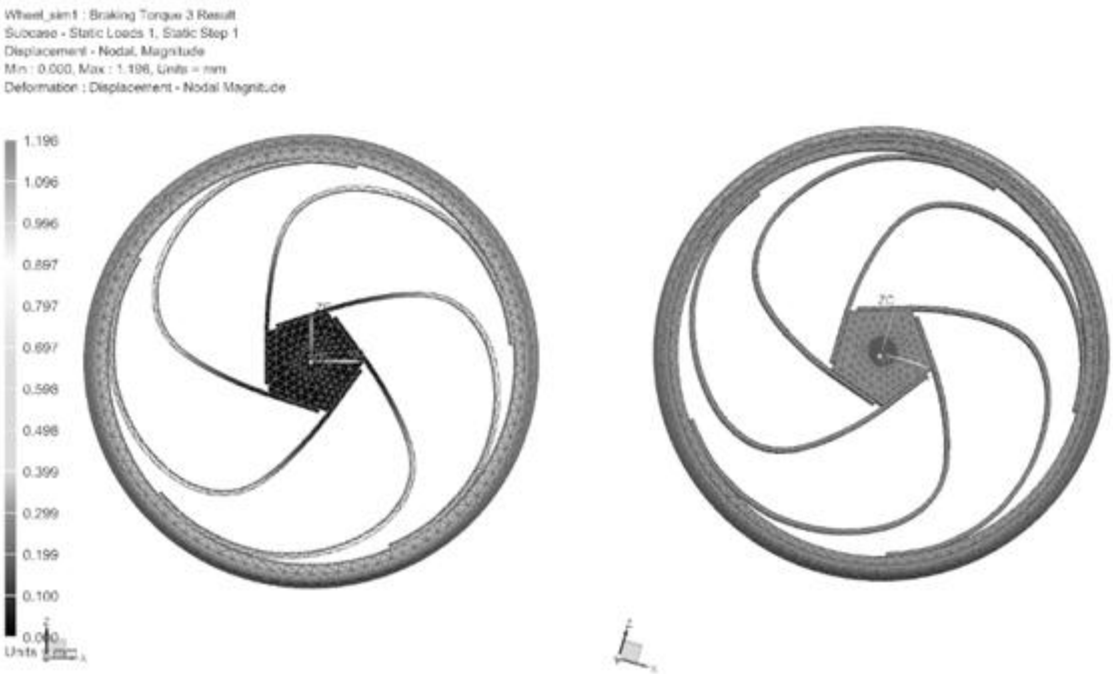

Figure 9 Scaled deformation of effect of braking torque

4. Effect of driving torque and combined weight is as shown in Figure 10. The maximum nodal stress generated i.e. 73.83 N/mm^2 is under Safe design stress limit for dynamic loading conditions i.e. 170 N/mm^2.

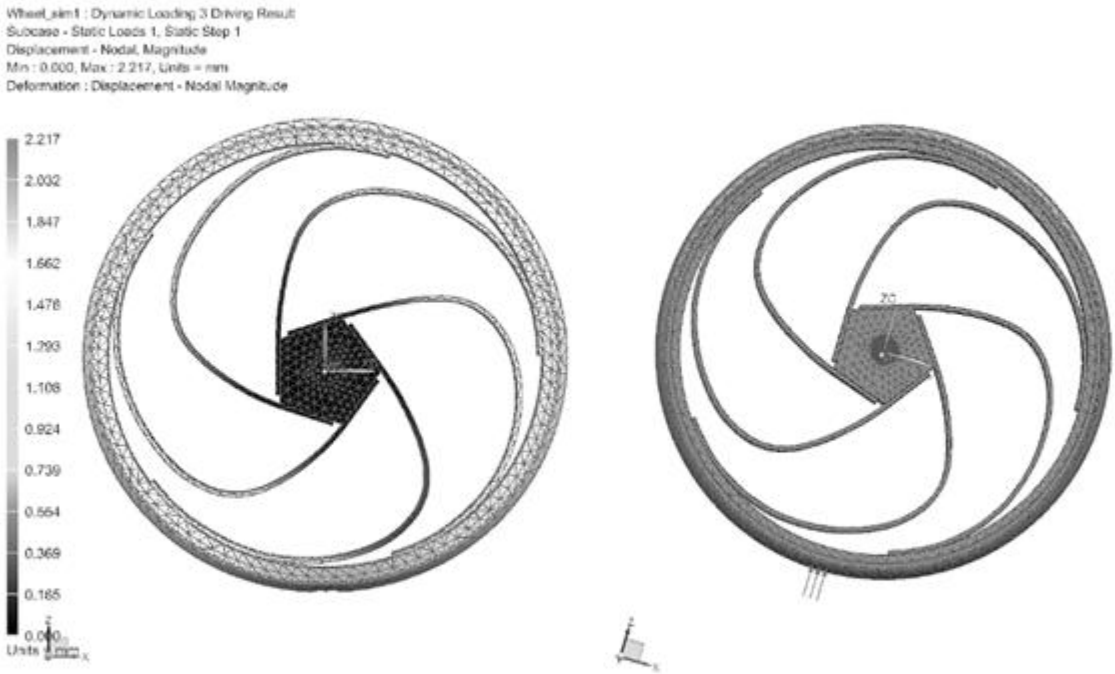

Figure 10 Scaled deformation of combined effect of driving torque and combined weight

5. Effect of braking torque and combined weight is as shown in Figure 11. The maximum nodal stress generated i.e. 88.81 N/mm^2 is under Safe design stress limit for dynamic loading conditions i.e. 170 N/mm^2.

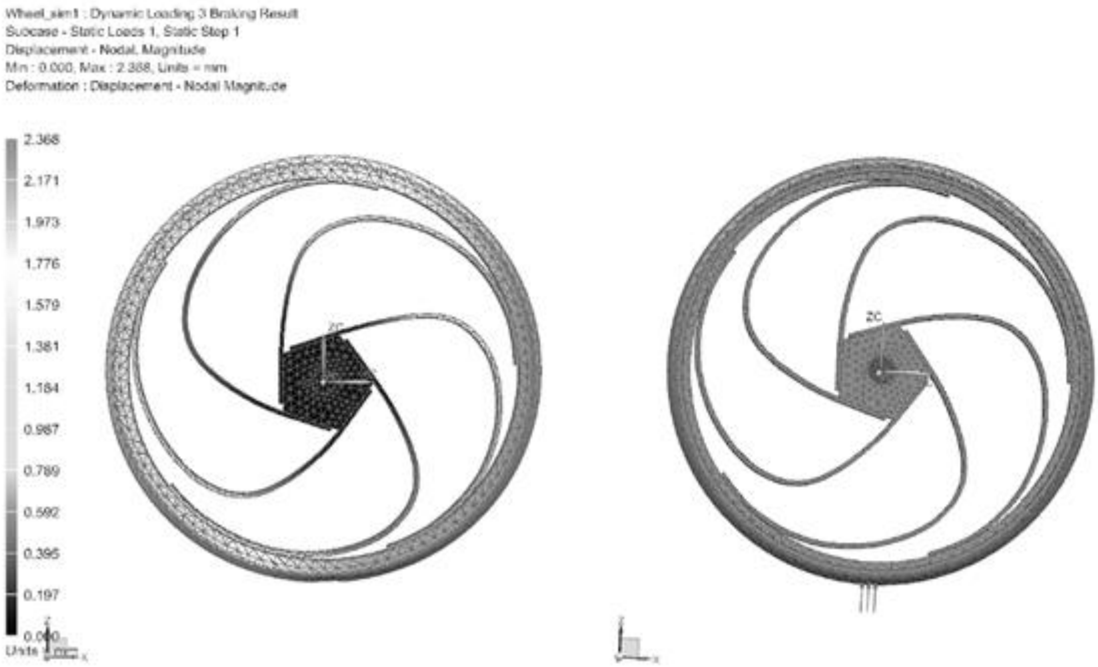

Figure 11 Scaled deformation of synchronous effect of braking torque and combined weight

VI. ABBREVIATIONS

m Mass of Rider
M_b Mass of Bicycle
M Total Combined Mass
W Total Combined Weight

g	Gravitational Acceleration
W_f	Total Weight on Front Bicycle Wheel
N_f	Normal Reaction Force on Front Wheel
N_r	Normal Reaction Force on Rear Wheel
S_{ut}	Ultimate Tensile Strength
S_{yt}	Yield Tensile Strength
σ	Safe Design Stress
F	Pedal Force
Ø	Angle of Inclination
F_s	Factor of Safety
C_{rr}	Co-efficient of Rolling Resistance
C_d	Drag Co-efficient
ρ	Density of Air
A	Projected Area of bicycle and rider.
P	Pedal Power
P_w	Power on Wheels
T	Pedaling Torque
T_w	Pedaling Torque
D	Diameter of Bicycle Rim
R	Radius of Bicycle Rim
N	Rotation per minute (RPM)
K.E.	Kinetic Energy of the Wheel
T.E.	Total Energy of the Wheel
I	Moment of Inertia of Wheel
E	Total Energy
v	Linear Velocity
u	Initial linear velocity
a	Linear Acceleration
t	Time
s	Distance
ω	Angular Velocity
ω_0	Initial Angular Velocity
α	Angular Acceleration
θ	Angular Distance
T_b	Braking Torque

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