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DEVELOPMENT OF REGENERATIVE BRAKING SYSTEM FOR BICYCLE USING FLAT SPIRAL SPRING

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Abstract- *Every transport vehicle has gone through a lot of modification with the passage of time due to invention of new technology, design and for fulfilling passengers demand. Bicycle too is not outside of this trend. Introducing transmission system, dynamo and disc braking system to the conventional bicycle as well as unveiling of electric bicycle into the market place are few examples. To keep this wheel going on, addition of regenerative braking system to the bicycle is just another successful attempt. In this paper, a new design of regenerative braking system for bicycle using flat spiral spring has been represented. While riding a bicycle, large amount of energy is lost during braking. To gain the speed once again, more physical energy is required. Using flat spiral spring, kinetic energy of the bicycle can be stored during braking action and this stored energy can be utilized to recover the speed after the brake lever is released. Thus, it will eliminate the loss of physical energy due to braking. The main objective of this research is to validate the proposed design. From the experimental result, it is found that the wheel of the model can quickly gain its speed after releasing the brake which suggests validity of the proposed design. Implementation of this new design can reduce muscle effort along with improving the efficiency of conventional bicycle without compromising the performance.*

Keywords: Regenerative Braking System, Flat Spiral Spring, Stress-Strain Analysis, Torque Generation.

1. INTRODUCTION

Invention of new technology and insatiable demand of human being has caused a huge pressure on the natural fuel resources recently. The outcome is such that these fuel resources are now questioned to their sustainability. Different environmental protection agencies have been putting their best effort to correct the environmental damage as well as establishing new sets of rules and regulations to help reclaiming the natural environment to its balance. In this present state of art, use of bicycle can greatly reduce the fossil fuel demands, greenhouse gas emissions, roadway congestion while improving the user's physical health. In this context, implementation of regenerative braking system in bicycle can make the ride even smoother and reduce the physical labor.

In ordinary vehicles when the brake is applied then sufficient braking torque quickly reduce the vehicle speed. As a result, the kinetic and mass potential energy (momentum) of the vehicles are dissipated in the form of heat energy due to the friction produced in the brake paddle and wheel (or a disc connected to the axle). Research shows that about 30% of the generated energy is wasted in this process [1]. Vehicles equipped with regenerative braking system can indeed solve this problem along with optimizing the mechanical efficiency of the vehicle. As figure 1 suggests, the main concept of regenerative braking system is that it will accumulate the kinetic energy in a short term storage system during the time of brake. Then it releases the stored energy which is converted back into kinetic energy to reclaim the speed of the vehicles.

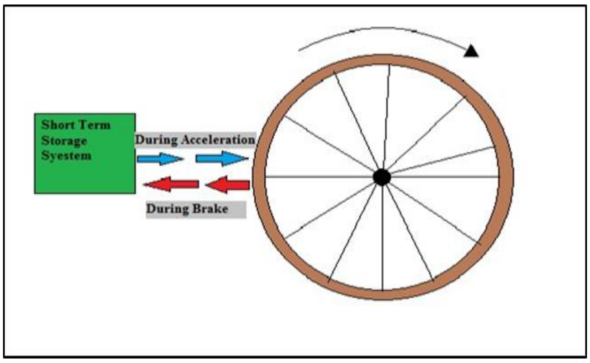

Fig.1: Basic principal of regenerative braking system

A lot of researches, attempts have been made on bicycle since its evolution. Being the most popular ride, people have put up their effort to reshape it according to their will. But the main attempt lies in reducing the physical labor which ultimately results in introduction of regenerative braking system. A group of students of Michigan University has created a prototype bicycle of 20" wheel featuring hydraulic regenerative braking system in the year 2009 [2]. The principle is to accumulate fluid oil in high pressure from a low pressure reservoir by means of a hydraulic pump during the braking action and then to release this energy to the power train by a hydraulic motor.

Another attempt was made on this topic where an innovative design of regenerative braking system has been proposed using compression spring as energy storing element [3].

In this field of study, a truly outstanding and successful attempt was “Flywheel bicycle” by Maxwell von Stein, an engineering student who won the Nicholas Stefano Prize at the annual event showcasing student projects by the famous Cooper Union [4]. In this bike a 6.8 kilogram flywheel from an automobile engine is mounted to a bicycle frame. This flywheel is linked to the rear wheel by variable transmission. During charge, the transmission is shifted to increase the ratio of flywheel speed to bike speed. During boost, it's shifted to decrease the ratio of flywheel speed to bike speed. The flywheel can store the kinetic energy temporarily from the bicycle and utilize it to regain the cruise speed after braking action. This provided 10% energy saving in pedal at a speed between 20 and 24 km/h.

Inspiring from the researches and attempts mentioned above, a new design of regenerative braking system for bicycle has been proposed in this paper and it is intended to develop a model which can validate the design. The main focus of this design is using flat spiral spring as energy storing element instead of fluid or other compression spring. The paper is organized as following manner. Section II represents the concept behind this design. Section III describes the proposed design of regenerative braking system. Section IV illustrates the model developed in light of the proposed design. Section V is devoted to model analysis and results. Lastly, section VI represents closing remarks and further recommendations.

2. CONCEPT GENERATION

Sufficient knowledge in bicycle is a prerequisite element to make a design of regenerative braking system. This includes different parts used in bicycle, basic mechanics behind the cycling, bicycle rear and front wheel system, power train mechanism and lastly the energy stored in the flat spiral spring. Thorough analysis of bike physics has led us to the following three major calculations. They are:

- Calculation of force required to move bicycle.
- Strain Energy Stored in Flat Spiral Spring.
- Torque generated in flat spiral spring.

2.1 Calculation of Force Required

Analysis of FBD of bicycle shows that just to move bicycle from stationary, it is needed to overcome rolling resistance force, which depends on the weight and co-efficient of rolling resistance. But while starting, the system is not in equilibrium with all the forces. That’s why this is not of much practical use. In order to determine the real force, the rate of acceleration at which bicycle is intended to move should be taken into consideration. Therefore, all of these conditions provide us with the following equation.

$$T = \frac{1}{R_w}(F_r + F_a + ma) \qquad (1)$$

Now to calculate the rolling resistance force following formula will be used.

$$F_r = c \times m \times g \qquad (2)$$

Lastly, to calculate the air drag force, the formula is as follow:

$$F_a = \frac{1}{2} \times C_d \times \rho_a \times v^2 \qquad (3)$$

2.2 Strain Energy Stored in Flat Spiral Spring

From the figure 2, it can be easily understood that when the inner end of the spring is wound the number of spiral in the spring is increased. This results in development of strain energy into spiral of the spring. This strain energy will be utilized to accelerate the bicycle once again. With the increase of spiral number, the radius of curvature of every spiral decreases. Therefore, the spring is subjected to pure bending. The strain energy developed in the spring can be calculated out by the following formula [5-6].

$$U = \frac{\sigma_b^2}{24E} \times b \times t \times l \qquad (4)$$

Fig. 2: Solidworks drawing of flat spiral spring.

2.3 Torque Generated in Flat Spiral Spring

As described in 2.2, when spiral spring is wound up then strain energy is developed. This strain energy provides torsion energy. Torque generated in a flat spiral spring is dependent upon several factors like length, breadth, thickness of the spring and the total number of deflection occurred in the spring.

Following formula provides the means to calculate the torque generated in a flat spiral spring [7].

$$M = \frac{\pi E b t^3 \theta}{6l} \qquad (5)$$

3. PROPOSED DESIGN OF REGENERATIVE BRAKING SYSTEM

After studying bicycle mechanics and torque generation capacity of a flat spiral spring, it is thus obvious that flat spiral spring can be utilized to provide acceleration to the bicycle. But there is a major drawback in this mechanism. If the mechanism of a flat spiral spring is analyzed then it can be found that after winding up the spring when it is

released then it gives the torque in the reverse direction. That is why in order to deliver the torque from the spring to the wheel of bicycle, there should be a mechanism by which the reverse torque can be directed towards the forward motion of the bicycle. Based on the concept described in the previous section and the specification mentioned, a design has been made. Figure 3 shows the proposed design of regenerative braking system for bicycle. This design consists of the following parts:
1. Five gears; out of which two gears have been modified, 2. Flat spiral spring, 3. Freewheel of bicycle, 4. Sprocket, 5. Shaft, 6. Bearing, 7. Bicycle wheel.

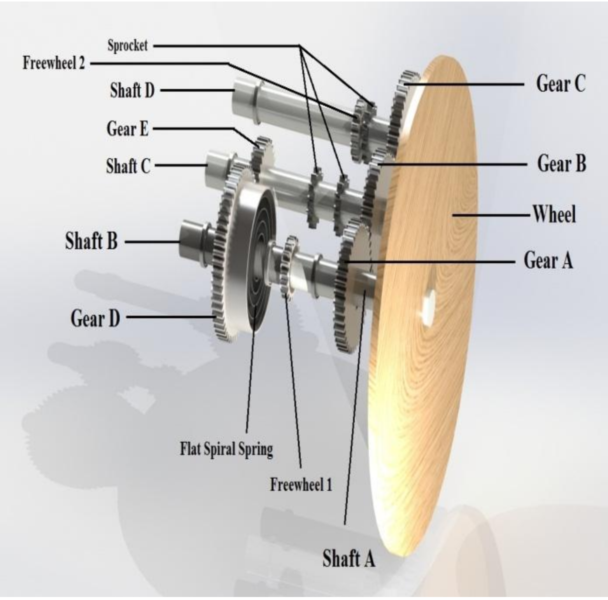

Fig. 3: Solidworks drawing of the proposed design

From the Figure 3, it is seen that there are total four shafts. The wheel, Gear A and the inner threaded part of the freewheel 1 are connected to the shaft A. Shaft B has connected with the sprocket of freewheel 1 and the inner part of the flat spiral spring. Outer part of the flat spiral spring is connected with Gear D. Gear D can move freely over the shaft B. A little modification has been made in the Gear B. First, a freewheel is taken and then the sprocket of the freewheel is connected with Gear B. As a result, Gear B will act just like a freewheel along with torque transfer function. Then, the threaded part of freewheel is connected with shaft C. As the figure shows, two sprockets and Gear E have been attached with shaft C. Lastly, the shaft D holds freewheel 2, one sprocket and Gear C. Freewheel 1 is to be connected with the sprocket on the shaft C by means of chain. Another sprocket on shaft C is connected with freewheel 2 by another chain.

3.1 Working Procedure

In normal driving condition, sprocket on the shaft C is connected to the freewheel 2. When the wheel starts rotating, Gear A will also rotate. This in turn will rotate the Gear B in anti-clockwise direction. Since Gear B has been modified into freewheel, the shaft C will not rotate. Now, the Gear B has been meshed with Gear C, which will result in rotation of Gear C as well as shaft D in clockwise direction. Shaft D has been connected with the freewheel 2 and due to ratchet mechanism no power will be transmitted from shaft D to shaft C although freewheel 2 is connected with the sprocket on shaft C by chain. Thus there will be no deflection in the flat spiral spring.
During the time of brake, the chain connecting the sprocket on shaft C and freewheel 2 will be shifted to the sprocket on shaft D. At this condition, shaft C will rotate in the same direction as shaft D i.e. clockwise direction. This in turn will rotate Gear E and the sprocket of freewheel 1. As a result, Gear D will rotate in anti-clockwise direction and shaft B will rotate in clockwise direction, which will cause the flat spiral spring to wind up. Thus the wheel will come to rest gradually.
In order to use the stored energy in flat spiral spring to accelerate the wheel, the chain has to be shifted once again. That means the sprocket on shaft C will be connected to freewheel 2. In this condition, the flat spiral spring will unwind resulting in rotation of shaft B in anti-clockwise direction and gear D in clockwise direction. Rotation of gear D and shaft B will ultimately rotate the shaft C in the anticlockwise direction through Gear E and chain respectively. As the shaft C rotates in anti-clockwise direction so is the Gear B. Finally, the torque will be provided to the wheel by Gear A.

4. DEVELOPMENT OF MODEL

The final model was developed according to the design presented in figure 3. The developed model consists of different parts and it involves specific operations for their development. Now the major parts used in this model and certain operation to develop those parts have been discussed below:

A. Flat Spiral Spring
Flat spiral spring that has been used in this model was manufactured. The arbor diameter of this spring is 1.5cm, thickness 1mm, length 1.5cm. The outer part of the spring was connected with the gear by spot welding as well as bolt joining. On the other hand, the shaft was cut up to requirement and then the inner part of the spring was inserted into the cut.

Fig. 4: Flat spiral spring enclosed in gear.

B. Modification of Gear

As the figure 3 suggests, some modification has been made in Gear B. At first, a freewheel was taken. Then the sprocket of that freewheel was joined with the gear by spot welding. As a result Gear B acts just like a freewheel along with its torque transfer function. This modification allows the shaft C to rotate in clockwise direction with the rotation of Gear B in the same direction. It will not create any interference in rotation of shaft C when Gear B rotates in anti-clockwise direction. At the same time it paves the way to transfer the power from spring to the wheel, when the shaft C rotates in anticlockwise direction.

Fig.5: Modification of gear

C. Alteration of Freewheel Attachment

Just like the proposed design shown in figure 3, freewheel attachment with shaft has been altered in the final model. The sprocket of freewheel 1 has been connected to the shaft B by spot welding and the inner threaded part of freewheel has been connected with shaft A.

Fig. 6: Alteration of freewheel attachment

Finally, when all the required parts were fabricated and purchased then the assembly was made to present the final model. Figure 7 shows the developed model after assembly was done.

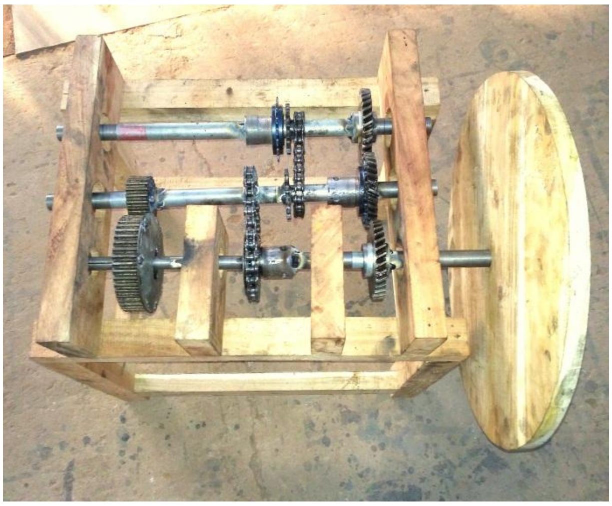

Fig.7: Developed model

5. MODEL ANALYSIS AND RESULTS

After reviewing the whole system and its components, some failure criteria were identified. It was found out that if the system model fails then the most probable cause would be bending or cracking down of the shaft connecting with the flat spiral spring. It is because while operating a resisting torque develops on the shaft. As a result, there is a chance of formation of angle of twist. With the increase of torque, the resisting torque increases too. Calculation shows that the developed model generates a maximum of 0.5 N.m torque. That is why stress and strain analysis was carried out on the shaft connecting to the flat spiral spring. First, an exact shaft was drawn in Solidworks. Then stress and strain analysis was carried out providing 0.1 N.m torque.

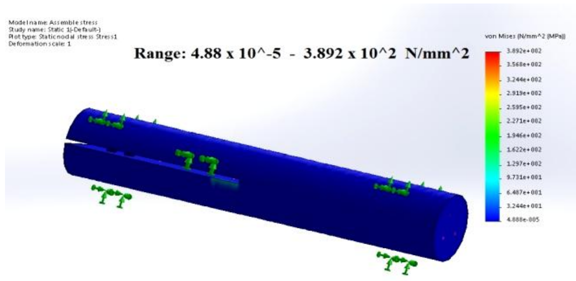

Fig. 8: Stress analysis for failure applying 0.1 N.m Torque

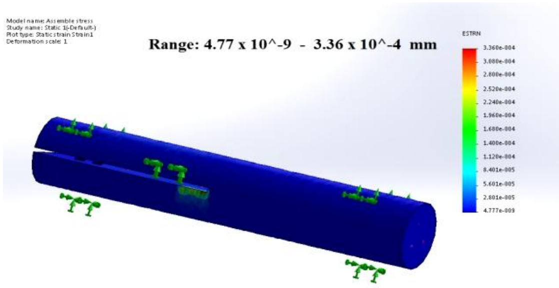

Fig. 9: Strain analysis for failure applying 0.1 N.m torque.

The process was repeated applying 0.5 and 1 N.m torque. Table 1 shows the result of model analysis.

Table 1: Results of stress and strain analysis

Provided Torque (N.m)	Maximum Stress (N/mm^2)	Maximum Strain (mm)
0.1	1.66×10^2	3.08×10^{-4}
0.5	1.028×10^3	1.247×10^{-3}
1	2.35×10^3	2.996×10^{-3}

From Table 1, it is found that on application of 1 N.m torque maximum stress developed on the shaft is 2.35×10^3 N/mm^2 which is greater than yield point. Therefore, at this point the shaft will bend or formation of crack will start.

Other than model analysis, performance analysis has also been carried out. It is found that the initial angular velocity of the wheel before applying the brake is 65 rpm. After applying the brake, the wheel comes to rest within 0.6 second. After releasing the brake, the angular velocity is measured to be 42 rpm.

From calculation, it is found out the input torque to be 0.376 N.m and the torque delivered to the wheel after releasing brake is 0.102 N.m. with an efficiency of 27%.

6. CONCLUSION

Regenerative braking system utilizes the braking energy to accelerate the vehicle. In this paper, a new design of regenerative braking system for bicycle using flat spiral spring has been presented which aim is to reduce muscle effort during braking action without compromising the efficiency. In this current situation when the whole world is facing a challenge against the sustainability of fuel resources, introducing this feature in the bicycle can attract more people towards its use. This can ultimately play a role in reclaiming the environment to its balance. Model analysis and experimental result confirms validity of the design proposed in this paper. Further analysis of this design concludes with the following recommendations:

- The design proposed in this paper requires a shifting chain mechanism. Installation of derailleur mechanism will enhance the controlling features a lot.
- This design presents the idea of regenerative braking system for bicycle. But installing this feature in fuel powered vehicle will reduce the fuel consumption rate up to 30-35%.
- In this model, gears made of cast iron were used. But use of fiber gear can reduce the noise during operation and it will not create any impact in the balance of the bicycle due to its lighter weight.

7. REFERENCES

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8. NOMENCLATURE

Symbol	Meaning	Unit
T	Torque of the wheel	(N.m)
R_w	Radius of the wheel	(m)
F_r	Rolling resistance force	(N)
F_a	Air drag force	(N)
m	Mass of the body (bicycle with the rider	(Kg)
a	Acceleration of the bicycle	(m/s^2)
c	Co-efficient of rolling resistance	Dimensionless
g	Acceleration due to gravity	(m/s^2)
C_d	Co-efficient of air drag	Dimensionless
ρ_a	Density of air	(Kg/m^3)
v	Velocity of the bicycle	(m/s)
U	Strain energy in spring	(N.m)
σ_b	Maximum bending stress induced in spring material	(N/m^2)
b	Width of strip	(m)
t	Thickness of strip	(m)
l	Length of strip forming the spring	(m)
E	Modulus of elasticity	(N/m^2)
M	Torque Generated in flat spiral spring	(N.m)
θ	Angular deflection in revolution	Revolution