Development of a Spoke-Less Bicycle Wheel Housing the Entire Prime-Mover Assembly for an Electric Bicycle

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Abstract: ***Electric bicycles or E-bikes are the future of transportation and have the potential to change the daily commute scenario in urban areas. E-bikes can not only contribute towards an environmental-friendly commuting option but also promote a fitter community. One of the reasons limiting the use of E-bikes is their cost (both capital and operating). To reduce the cost of E-bikes, a system needs to be developed that would allow the easy conversion of any ordinary bicycle into an E-bike. This can be achieved by designing an external electric drive train or a prime-mover assembly that can be installed onto any bicycle without disrupting its mechanical transmission. This paper describes the development of a prototype which can be used for the conversion of any regular bicycle into an E-bike by replacing its front wheel. Since the front wheel is not an active member of the mechanical transmission and can be easily removed, it can house an entire prime-mover assembly. The front spoke-less wheel of the prototype houses a motor, a battery and two idler pulleys in a triangular formation. The rear transmission is left unchanged leaving the option of riding the bicycle with or without the electrical components. The power from the motor is directly transmitted to the inner rim of the front wheel using the friction-drive. The speed is controlled by a throttle integrated into the handlebar. The outcome of the development phase is the conversion of an ordinary bicycle into an E-bike that provides a stable riding experience with proper balancing of forces in the front wheel and optimum power availability for the rider.***

Keywords: electric bicycles, E-bikes, prime-mover assembly, spoke-less wheel

1. Introduction

An electric bicycle or an E-bike is any traditional bicycle with the addition of an electric motor to propel the vehicle or assist the rider. The electric motor is powered by a rechargeable and/or removable battery [1]. With the advent of light-weight motors, highly efficient batteries and developments in bicycle components, today's electric bicycles have made it possible for a broad array of people, irrespective of age, gender, health condition or skill to appreciate the numerous benefits of cycling [2]. Electric bicycles, as a new form of personal transport, are an innovative approach to urban transport in countries with large populations and in countries which are concerned about the environment [3].

Electric bicycles are being increasingly used by people around the world due to their many benefits, but they are not without their problems. E-bikes are generally more expensive than regular bicycles or even conventional two-wheelers [4]. This cost can reduce drastically if any regular bicycle could be converted into an E-bike. This paper discusses the development of a portable electric transmission that could be easily installed onto any bicycle to transform it into an E-bike.

2. Literature review

A motor and a rechargeable battery are essential for any electric bicycle. The most common types of electric bicycles in the market are mid-drive, where the motor is installed in the middle of the bike, usually where the pedals are positioned and hub-drive, where the motor is installed either on the rear or front wheel-hub [5].

Positioning a motor in the middle of the bicycle or in a wheel-hub increases the unsprung weight of the vehicle (weight below the mid-point of the vehicle's suspension). Since, most bicycles do not have a proper suspension system, the jerk from the road is handled by the frame, which makes unsprung weight even more undesirable in a bicycle. Additionally, the supplementary weight brought by their electric drivetrains changes the suspension geometry of the vehicle [6]. Thus, it is ineffective to install a motor at either of these locations.

2.1 Considerations for prototype development

The two major considerations for the easy conversion of a regular bicycle into an electric bicycle are that the electric drivetrain must not interfere with the pre-existing mechanical chain-drive system of the bicycle and that the drivetrain assembly must be compact enough to be installed onto any bicycle. In addition, the electric drivetrain must not de-stabilize the operation of the bicycle.

Since the front wheel of any normal bicycle is not an active member of its chain-drive transmission system, it is the easiest part to remove or replace. Therefore, the complete electric drivetrain including the motor, controller and the batteries can be installed inside the front wheel.

3. Concept development

The only conceivable way to integrate a motor, a battery and a controller with a bicycle wheel is to remove the spokes and the insides of the wheel. The spoke-less front wheel can accommodate a motor and two idler pulleys in a triangular formation (based on a planetary gear arrangement) as illustrated in Figure 1. The idler pulleys are added to balance out the normal force from the ground onto the wheel and to stabilize the outer rim. The only part that needs to be attached separately from the wheel is a simple hand-activated throttle, which can be easily clipped onto the bicycle's handlebar. Friction-drive can be used for power transmission due to its ease of manufacturing and fewer moving parts.

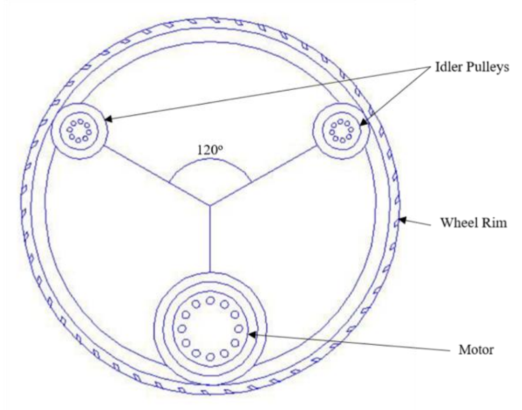

Figure 1: Final 2-D design for the front wheel

3.1 Transmission design

The electric transmission for this spoke-less front wheel will consist of a motor which will transfer its energy to the outer rim of the wheel using friction-drive (like a belt drive). The outer wheel rim will be machined to a V-shaped cross-section (as illustrated in Figure 2) so that it can mate with the V-shaped groove on the motor and the idler pulleys (as shown in Figure 3).

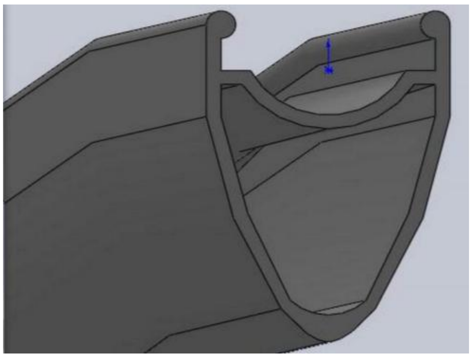

Figure 2: V-shaped Double Walled cross-section of the Wheel Rim

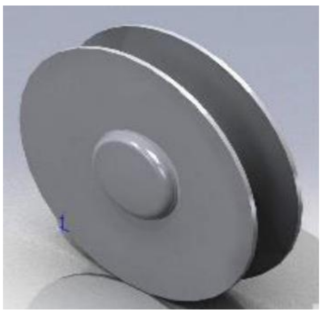

Figure 3: V-shaped groove on the idler pulleys

3.1.1 Friction-drive transmission

The following parameters were considered in the selection of the transmission system.

- The transmission system must be easy to manufacture and mount onto a single spoke-less wheel rim.
- The transmission must not require any pressurized lubrication.
- The transmission must be able to transmit high torques.
- The transmission system must be easy and economical to manufacture.

Due to the high cost involved in the manufacturing and the of a geared transmission.

3.1.2 Calculation of the tractive force, torque and required power

To calculate the tractive force to propel the bicycle, the following assumptions were made,
Total weight (rider + vehicle) (m) = 150kg
Desired top speed (v) = 25km/h = 6.94m/s
Time required to accelerate to top speed (t) = 15s
Coefficient of rolling friction (μ_R) = 0.004
Radius of bicycle tire (r) = 311mm = 0.311m
Acceleration due to gravity (g) = 9.81m/s^2

We know that, the tractive force required to drive the bicycle is,

$$F_{Tractive} = F_{RR} + F_{GR} + F_{Inertial} + F_{AD} \quad (1)$$

where,
$\boldsymbol{F_{RR}}$ is the rolling resistance
$\boldsymbol{F_{GR}}$ is the gradient resistance
$\boldsymbol{F_{Inertial}}$ is the force required to overcome inertia
$\boldsymbol{F_{AD}}$ is the force due to aerodynamic drag

Considering F_{GR} and F_{AD} to be negligible, Equation (1) becomes,

$$F_{Tractive} = F_{RR} + F_{Inertial} \quad (2)$$

Now,

$$F_{RR} = \mu_R mg \quad (3)$$

$$F_{RR} = (0.004)\,(150)\,(9.81)$$

$$F_{RR} = \mathbf{5.886N} \quad (4)$$

Also,

$$F_{Inertial} = ma \quad (5)$$

$$F_{Inertial} = (150)\,(6.94/15)$$

$$F_{Inertial} = \mathbf{69.4N} \quad (6)$$

From Equations (2), (4) and (6), we get,

$$F_{Tractive} = \mathbf{75.286\ N} \quad (7)$$

Therefore, torque required to drive the bicycle ($T_{Tractive}$),

$$T_{Tractive} = F_{Tractive} \times r \quad (8)$$

$$T_{Tractive} = (75.286)\,(0.311)$$

$$T_{Tractive} = \mathbf{23.41Nm} \quad (9)$$

Considering the efficiency (η) of power transmission to be 90%, the power required to achieve the tractive force is,

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$$P = \frac{F_{tractive} v}{\eta} \quad (10)$$

P = (75.286) (6.94) / (0.9)

P = **580.54 W** (11)

3.1.3 Selection of the motor and the battery

Based on Equations (9) and (11), a Brushless DC (BLDC) motor with a power output of approximately **600W** and constant torque of **23.41Nm** should be selected for this prototype. To keep the weight of the front wheel to a minimum, we need to use a lithium-ion battery. To power the motor, a battery of **48V** and **15AH** lithium-ion is required.

3.2 Structural Design

The structure of the wheel consists of two major components: the wheel rim and the frame structure.

3.2.1 Wheel rim design and material selection

The following considerations were made while designing the spoke-less wheel rim.

- The wheel rim for this application must be able to bear the high torque which will be directly transmitted to it through the motor periphery.
- The wheel rim must have a cross-section like V-belt (see Figure 2), so that it fits onto the groove machined onto the motor and the idler pulleys (see Figure 3).
- The cross-section must be hollow to reduce the weight of the rim.
- The rim must have a smooth braking surface to facilitate the use of rim brakes.
- The material of the rim must be sturdy enough to bear the weight of the motor and stabilize it during operation.
- The material of the rim must be hard enough to resist any surface damage due to the friction from the motor and the idler pulleys.
- The design must be easy and economical to manufacture.
- Other considerations are mass and inertia, durability, brake compatibility, tubeless tire compatibility and cost.

Based on the considerations, a standard double-walled rim can be designed (as shown in Figure 2) as it would provide the required stiffness and structural stability while being hollow. The dimensions for the wheel rim cross-section are as shown in table 1 and Figure 4.

Table 1: Dimensions of the wheel-rim cross section

Dimension	*Value*
Width (w)	30 mm
Length (l)	50 mm
Thickness (t)	7 mm
Radius (r)	311 mm

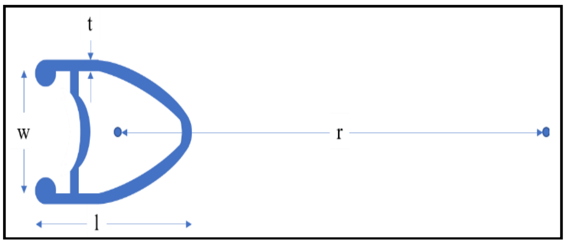

Figure 4: Cross-sectional dimensions for the rim

Aluminum 2024-T4 can be used as the material for the rim because this material is commonly used for high-performance cycling operations and fulfils all our considerations.

Table 2: Aluminum 2024-T4 properties [7]

Property	*Metric*	*Comments*
Density	2780 kg/m^3	
Hardness, Brinell	120	500g load; 10 mm ball
Modulus of Elasticity	73.1 GPa	
Poisson's Ratio	0.33	
Machinability	70%	0-100 Scale of AluminumAlloys

3.2.2 Frame design and material selection

The following parameters were considered while designing the spoke-less wheel rim.

- The material of the frame must be lightweight, but sturdy enough to bear the weight of the controller, battery and the motor and stabilize them during the operation.
- The frame must be able to bear the normal reactions from the terrains and the torque transmitted by the motor.
- The design must be easy and economical to machine.

Based on the considerations, the following CAD renders were made for the frame on SolidWorks and Autodesk Fusion 360 (as illustrated in Figures 5 and 6). The frame was designed to be cut out of a single sheet of aluminum and cutouts were made to reduce the overall weight of the frame. The dimensions are shown in table 3 and Figure 7.

Table 3: Dimensions of the frame

Dimension	*Value*
Length (l_1)	305 mm
Length (l2)	232.5 mm
Thickness of aluminum sheet (t)	80 mm

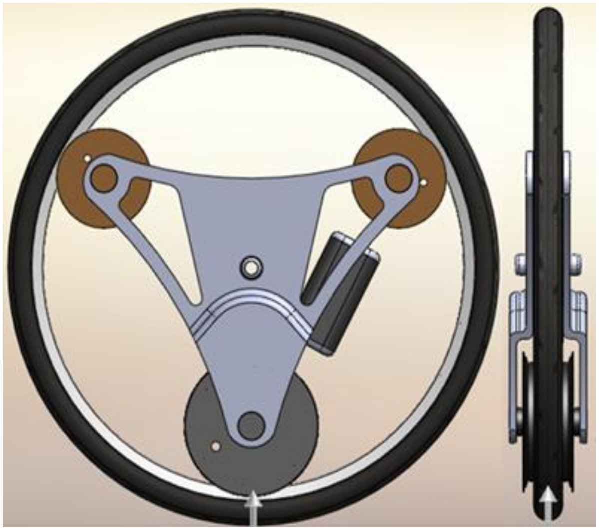

Figure 5: Frame design – front and side view

Figure 6: Frame design – isometric view

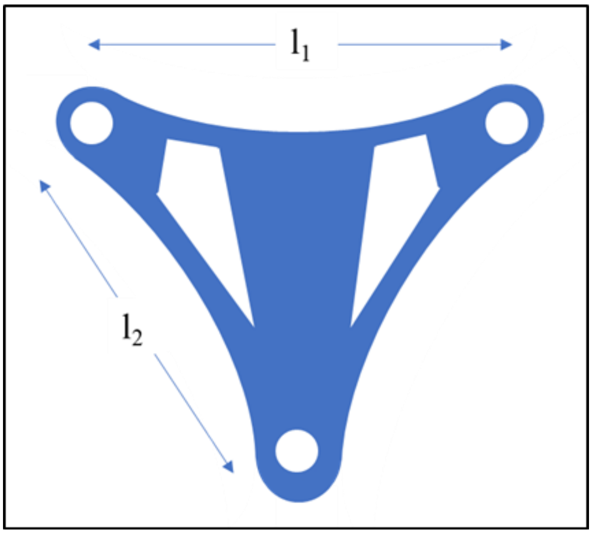

Figure 7: Dimensions of the frame

Aluminum 6061-T6, which is an alloy of aluminum, magnesium and silicon was chosen as the material for the frame. It is easier to handle and machine. Also, it provides the appropriate stiffness to the frame while being lightweight.

Table 4: Aluminum 2024-T4 properties [7]

Property	*Metric*	*Comments*
Density	2700 kg/m3	
Hardness, Brinell	95	500g load; 10 mm ball
Modulus of Elasticity	68.9 GPa	
Poisson's Ratio	0.33	
Machinability	50%	0-100 Scale of Aluminum Alloys

3.2.3 Design of motor and idler peripheries

The motor periphery needs to be machined into the same V-shaped cross-section as the rim as shown in Figure 8. To generate enough friction between the rim and the motor, the motor needs to be covered with a plastic or rubber component. The dimensions are shown in table 5 and Figure 8.

Table 5: Dimensions of the motor periphery and idler pulleys cross-section

Dimension	*Value*
Width (w)	30 mm
Length (l)	35 mm

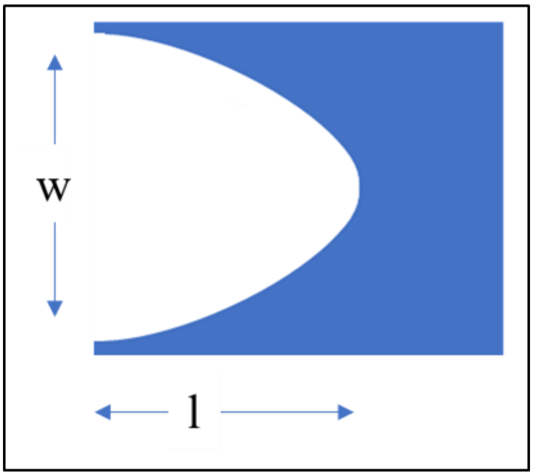

Figure 8: Cross-section of the motor and the idler pulleys

Based on applications requiring similar torque, polypropylene (PP) was selected as the material for the layer.

The idler pulleys need to have a similar cross section as shown in Figure 8. They can be fabricated of the same material as the motor periphery. This will help maintain the same level of friction between the rim and the idlers.

3.2.4 Selection of the tubeless tire

Based on the application, any tubeless tire or solid tire can be selected. The diameter for the tire is **622mm** and the tubeless tire is shown in Figure 9.

Figure 9: Tubeless tire for the rim

4. Prototyping

Due to budget constraints, the prototype was different from the initial design. The prototype was manufactured over a period of two months and the stages have been outlined below.

4.1 Machining of the motor and idler peripheries

The outer V-groove for the motor was machined with a lathe machine. The motor groove was mated with the rim (as shown in Figures 10 and 11).

Figure 10: Outer V-groove of the motor

Figure 11: Mating the motor and the rim

The idlers were machined from polypropylene shafts (as shown in Figure 12).

Figure 12: Idler pulleys with a V-groove periphery

4.2 Machining of the frame

The frame was machined from a sheet of Aluminum 6061-T6 using a CNC. A mechanism was developed to slide the motor easily onto the frame without the use of a bolt. A knob was machined which could be turned with bare hands to disconnect the motor from the frame (as shown in Figure 13).

Figure 13: Connecting the frame with the motor

4.3 Assembly of the prototype

A mechanism was developed to slide the frame easily onto the wheel. A sliding joint helps slide the frame off the rim (as shown in Figure 14).

Figure 14: Sliding Mechanism

The rim and the frame were assembled (as shown in Figure 15).

Figure 15: Frame and Rim assembly

A tubeless tire was installed on the assembly (as shown in Figure 9).

The throttle for the motor was positioned on the handlebar (as shown in Figure 16).

Figure 16: Throttle installed on the handlebar

The assembly was connected to a traditional cycle (as shown in Figure 17).

Figure 17: Wheel installed on a traditional bicycle

Figure 17 represents the final prototype.

5. Limitations

These are some of the limitations of the prototype.

5.1 Slippage

Slippage occurs when the applied tractive force is more than the traction available to the mating surfaces. During the start-up of the prototype, the motor produces more than the required amount of torque, which results in slippage of the rim over the motor groove. Also, on gradient surfaces, there is slippage due to loss of contact between the motor and the rim.

5.2 Acceleration

The prototype attains its top speed of 25 km/h in roughly 15 seconds, which gives us an acceleration of approximately 0.46 m/s2. The time for acceleration can reduce significantly if the rider pedals along with the accelerating motor. Hence, there is a need to improve the acceleration of the prototype, which can be achieved by using a higher torque motor.

6. Future Scope

Some improvements can be made in the prototype and have been discussed below.

6.1 Braking improvements and regenerative braking

The prototype uses rim-braking like a traditional bicycle and is sufficient to handle speeds of approximately 25-30 km/h. However, if the top speed of the bike were to increase, this would be inefficient. A solution to this may be motor-braking or regenerative-braking. Additionally, the regenerative braking system would conserve energy and improve the range of the prototype.

6.2 Gradients

To ensure optimum performance on higher gradients (greater than 10°), more tractive torque needs to be generated, which would mean a more powerful motor. But, at high torques, there may be chances for slippage. Consequently, there will also be the need for a more efficient version of the friction-drive transmission.

6.3 Frame strength and suspension design

The current frame does not incorporate any suspension elements in it and may cause disturbances in the transmission due to high loading or extended use. Therefore, a suspension system can be designed and unified with the existing frame, which would also result in better frame strength for the prototype.

7. Acknowledgement

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