ABSTRACT

In recent years, many attentions have been paid on global environmental protection and energy saving; more people, therefore, have chosen bikes for commuting to work or school. For longer distance transportation and less effort, electric power assist bikes have re-entered the market. Due to regulation of some countries, electric bikes that must be pedaled were developed. These machines utilize the pedals as the dominant form of propulsion, with the motor used only to give extra assistance when needed for hills or long journeys. The ratio of electric power to human power may affect the riding feel. As a result, a torque sensor, which detects the pedaling force, is crucial in this application. This paper proposes a new design of torque sensor by way of twist angle measurement. It is composed of a torsion bar, input and output shaft with ring magnets and Hall sensors to achieve contactless sensing. It can be integrated with the rear wheel hub or the bottom bracket to detect the pedal force exerted on the chain. By selecting pole pairs of the ring magnets, the pedal position can also be obtained through the simple look-up table. This additional information can be used to identify the special situations to avoid the unwanted assistance. The mechanical design method and signal processing algorithm are discussed in this paper. Furthermore, the prototype sensor was implemented in a test bike as well.

INTRODUCTION

An E-bike is a bike which can supply riders with assist power by actuating motor. In the 1890s, electric bikes were documented within patent. Ogden Bolton Jr. was granted U.S. Patent 552271 [1] for a battery powered bike with “6-pole brush-and-commutator direct current (DC) hub motor mounted in the rear wheel.” Hosea W. Libbey invented an electric bike [2] that was propelled by a “double electric motor.” The motor was designed within the hub of the crankset axle. At that time, E-bike was controlled as simple as an on-off switch button.

Using sensors to control the motor for assisting power was developed in the late 1990s. Chin-Yu Chao filed a patent [3] in 1998 for such a device. The bike has a pedal force sensor for detecting the displacement of crankset axial. The sensor outputs a voltage signal representing the magnitude of the pedal force.

After a long term development, the technique of providing assist power can be divided into two types: independence and proportion. The difference between these two types is the relation with the pedaling force and the assist power which provided by motor. The independence type E-bike provides assist power by controlling the magnitude of the throttle mounted on the handlebar. People can operate the throttle for the assist power as riding on motorcycle.

The other type of E-bike provides proportional assist power according to the force that rider pedals, also called pedelec. To compare with the independence type, the pedelec has following advantages:

1. It keeps the characteristic of biking, which means riders wouldn’t be trained to make a new riding habit. Furthermore, riding a pedelec is more comfortable.

2. Since the human and motor inputs are coupled, the batteries which a pedelec needs are less and smaller than the independence type’s.

Due to the safety and distinguishing them from motorcycle and scooters, many countries have enacted electric bike laws to regulate the use of electric bikes. In Europe, an E-bike, which is defined as meeting EU standard EN15194, has a motor of no more than 250W of continuous rated power and is only to be activated by pedaling [4]. As well as in Japan, electric bikes are treated as human-powered bikes [5]. Since the pedelec is safer and environmental friendly, it comes to be the development trend of E-bikes.

The key part of a pedelec is the power assist system. It has a sensor which can sense the rider pedaling force on the bike and send signal to an electric control unit (ECU). The ECU will determine the assist force value and provide the rider with power by driving the motor. The pedelec also has a battery package assembled on it for helping the rider with increasing the distance of transportation. The composition of the power assist system is shown in Figure 1.
The design of a pedelec could focus on the following directions [6]:

1. The control logic of the power assist system: The system needs to couple these two power source form, pedaling and motor. Besides, it should be driven and controlled in a way that it neatly follows the commands of the rider.

2. Design of failure mode: Because the pedelec has no independent power source, the mechanism and the control logic must insure the function whatever one of them is broken.

3. External appearance: The power assist system should be packed compactly into the frame and have an artistic look in order to match the higher price than traditional bike.

TECHNIQUE OF TORQUE AND ANGLE MEASURE

For the purpose of giving riders a product with comfortable riding characteristics, choosing and designing the sensor technology are important. Traditional art usually detect angle displacement of chainset for sensing the riding behavior. This technology has benefit of simple mechanism and competitive cost. But using angle detecting technology would not accurately determine the force that the rider treads on the pedals, it might happen that rider needs more assist power but the motor does not be activated since there is no angle displacement between the chainset and the body frame. This situation usually happens to climbing hill. In addition, the assisting power is not provided immediately. The motor is not activated until the rider steps on a crank of the bike over a half of a circular spinning movement. As a result, the rider still uses great effort to ride on the bike as before.

For solving such problems, detection devices which can detect both twisting torque and angle of a shaft have been shown. For example, Bourn Inc. points out a position and torque sensor, of which the components are shown in Figure 2. The detection device has an input shaft 1 and an output shaft 2, which are connected with a coupler. The detection device has three ring magnets and four Hall effect sensors. When the ring magnets revolving, the Hall sensors set next to those will have the potential variations and generate a digital output.

Figure 2 – The position and torque sensor of Bourn Inc.

Figure 3 shows a digital output result of a Hall sensor as an example that detects a revolving ring magnet with two pole pairs [7]. For a N pole pair ring magnet, N pulses per revolution can be obtained.

Figure 3 – The digital output result of a Hall sensor

The ring magnet 2 and 3 are N magnetic pole pairs, and the arrangements of north poles (N) and the south poles (S) which arrayed in these two rings are identical. Since the coupler is designed to flex, when there is a torque applied on either shaft, there is an angular displacement between the shaft 1 and 2. The Hall sensors detect the potential variations of ring magnet 2 and 3, and, as a result, there is a shift between these two digital outputs.

Figure 4 shows that when the shaft 1 shifts an angle displacement, the digital output cure of ring magnet 2 has been shifted. According to the difference of voltage dV, a twisting torque exerted can be calculated.
For detecting angle, the sensor needs the ring magnet 1 which has N+1 magnetic pole pairs. When the shaft 1 rotates, the Hall sensor can detect the magnetic field of the ring magnet 1 and 2. According to the different arrangement of the pole pair, the digital waveforms of ring magnet 1 and 2 are shown in Figure 5.

The wave 1 and 2 which produced by the ring 1 and 2 start with the same pole, as the shaft 1 begins to revolve, the voltages of wave 1 and 2 become different due to the difference of waveform, when the shaft 1 finish a complete rotation, the voltages come with the same value. The wave 3 is produced by a phase difference detector that calculates the phase difference between wave 1 and 2. The angular detection of the shaft 1 will be achieve by determining the voltage variation of wave 3.

The technology of this patent shows the device needs at least three magnet arrays to achieve the detecting action. It causes the sensor is hard to be manufactured and high cost. Moreover, the magnetic fields between the three magnet arrays may interfere with each other, such that the detection result may not be accurate.

**METHODOLOGY OF DETECTION WHICH USING TWO MAGNETS**

Since that detecting angle and torque at same time needs complex and plenty of sensors, the purpose of this paper is to provide a compact detection apparatus. The detection apparatus proposed has simple structure and detects the torsion and the rotational angle at the same time.

This methodology uses two ring magnets, two Hall sensors and a controller. The conceptive operation is shown in Figure 6. The two ring magnets 231, 232 are respectively mounted on a torsion shaft 20. In this example, the ring magnet 231 has two pole pair, and the ring magnet 232 has one. When the torsion shaft rotates, the controller 30 detects the magnetic fields of the two ring magnets through the two Hall sensors 241, 242. These sensors are aligned with each other and detect the magnetic fields which produced by ring magnets for generating their potential variations. There are a twist angle table 33 and a twist torque table 34 stored in controller.

When the shaft revolves completely circular movement (360 degrees) and the backward torque (Tc) of shaft is zero, the controller traces out two signal waves A and B, as shown in Figure 7, by detecting the potential variations of two ring magnets. Since there are two pole pairs in ring magnet 231, wave A is composed by four periods of sine wave, and wave B is a sine wave which has one period.

**Figure 4 – The phase difference of Hall sensor digital outputs**

**Figure 5 – The digital waveforms of ring magnet 1 and 2**

**Figure 6 – The contactless torque and angle sensor for electric power assist bike**

**Figure 7 – The potential waves of first and second magnet while the shaft rotates 360 degrees**
Every angle displacement of the shaft can correspond to a set of voltage information which is composed of wave A and B. Since each of the voltage information is non-repetitive, this information can be used to detect the angle displacements. The waveform of wave A and B are under the condition that the backward torque (T_c) of the shaft is zero, and recorded on the potential mapping table of the controller.

When exerting a force on the shaft, the backward torque (T_c) is not zero, there is a twist angle between the extremities of the shaft, then the ring magnet which mounted on the shaft also revolves, after all, this movement will cause the phase of potential which detected on the moving ring magnet to shift. An example is shown in Figure 8.

In this case, the first potential is shifted to 2.9V as plotted at point y from the original potential which recorded in the controller of 2.3V as plotted at point x, and a potential difference (ΔV) between the points x and y is 0.6V. The controller stores a twist angle table which established based on the relationships between potential differences (ΔV) and twist angles (Δφ). While the twist angle is obtained, the twist torque of the shaft can be represented by the equation 1.

\[ θ = \frac{TL}{GI} = \frac{4TL}{Gr^4π} \]  

(1)

where G expresses the shear modulus, and T is the torque which exerts on the shaft, the moment of inertia is expressed by I. The equation shows that the twist torque can be calculated if the twist angle is known. As a result, the controller correctly recognizes the twisting torque exerted on the shaft unit.

**THE DESIGN OF TORQUE/ANGLE SENSOR AND TESTING**

For applying the sensor to pedelec bike, the first step is considering where the sensor is placed. There are two axial shaft that the rider input his pedal force. One is bottom bracket, and the other is rear wheel hub. The assembly of the bottom bracket and the body frame is shown in Figure 9.

It shows that the pedals are attached on the chainset, which is also fixed on the bottom bracket. The bottom bracket is connected to the body frame with a revolute joint.

The paper assumes that the bike and the wheels are static before the rider pedals it. Therefore, the chainset and the bottom bracket are regarded as Link 1, and body frame is the Link 2. A revolute joint connects Link 1 and Link 2. There are two choices for replacing or adding a flexible member such as a torsion bar in this assembly. One is replacing the bottom bracket by torsion bar, and the other is adding a flexible member between the chainset and the pedal. These two ideas are shown in Figure 10.

However, because the chainset is connected with the rear wheel hub, if the rider pushes the right pedal, the force will be transferred to the rear wheel directly. Accordingly, the torsion bar might not be twisted for causing the angular displacement. In other words, the detector can not measure the torque while the rider pushes the pedal in fact.

When the flexible member is added in the chainset, the pedal force can cause the angle displacement between the chainset and the bottom bracket. As a result, the displacement of the flexible member can be caused by the pedal force from both the right and the left side. On the other hand, the challenge of this art is how to install the sensor in the limited space.

Considering the design of a detector with simple mechanism and without the problem abovementioned, a torque and angle sensor integrated with the rear wheel hub is proposed in this paper. The mechanism can be represented as Figure 11.
The detailed design of the sensor is shown in Figure 12. A compound shaft is mounted in the rear wheel hub and has Left Shaft with Ring magnet 1, Right Shaft with Ring magnet 2 and a torsion bar. Right Shaft is also mounted with the ratchet. Two Hall sensors are fixed stationary on the body of the bike corresponding to the two ring magnets.

When the rider exerts force on the pedal, the chainset transfers torque to the ratchet, and the torsion bar is twisted. As a result, there is relative angular displacement between the two ring magnets which can be regarded as a phase shift of zero torque position. The variation can be calculated by the proposed method.

In order to determine the stiffness of the torsion bar of the prototype sensor, the pedal force of the regular riding were measured during the test by installing the load sensors on pedals. The test result is shown in Figure 13. While the bike started to move, the pedal force reached maximum.

In this case, the maximum force is 500 N, and the radius of the chainset is about 200 mm. For distinguishing the riding situations, the maximum torque which the torsion bar can handle is set as 100 Nm. Furthermore, the angular displacement of the torsion bar should be limited. If not, the rider will feel an idle stroke. A mechanical stop was designed to make the angular displacement between the two shafts below 3 degrees. The prototype is shown in Figure 14.

To evaluate the effect of the proposed approach, the experiment was conducted. The torque and angle sensor was installed in the rear wheel hub as shown in Figure 15. The rider rode the test bike and the sensor detected the angle and torque at the same time.

Figure 16 shows the results that the rider pedaled over one turn from 0 to 360 to 270 degrees. The torque reaches 90 Nm at 1 sec and remains during the ride. The torque decreases when the chainset stop moving and the rider’s foot left the pedal.
CONCLUSIONS

The detection method of the proposed sensor has simple structure because of using just two ring magnets to detect the torsion and the rotational angle at the same time. It has following benefits for pedelecs and other power assist systems.

1. Performance: The sensor can detect the torsion and the rotational angle at the same time. More information can be provided for the controller of the power assist system, and smoother assistance can be achieved.

2. System composition: Due to less need of magnets and sensors, the cost of the sensor can be reduced.

REFERENCES

4. European Committee for Standardization, EN15194 for electric power assist bicycle, EU, 2009
7. Honeywell Sensing and Control, Hall Effect Sensing and Application.