An eight-speed rear transmission hub with a novel cam-type gear-shifting mechanism for bicycles

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ABSTRACT

In this study, the conceptual design of an eight-speed rear transmission hub with a novel cam-type gear-shifting mechanism for bicycles is proposed. The main body of the transmission hub is a distributed-flow type planetary gear mechanism to provide eight forward gears. A design process for the embodiment design of a rotary-type gear-shifting mechanism is presented and illustrated. By combining the planetary gear mechanism with the gear-shifting mechanism, a novel eight-speed rear transmission hub for bicycles is generated. A 3-D printed prototype is also manufactured for further testing.

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1. Introduction

Current speed changing devices for bicycles are generally of two main types: the exterior chain derailleur and the interior rear transmission hub.[1] The classical exterior derailleur moves the chain between sprockets with different numbers of teeth by a chain shifting mechanism to provide the rear wheel with different speed ratios (SRs), output torque, and angular velocity. The rear transmission hub uses a planetary gear mechanism as the main body to change the SR at each gear stage. The exterior chain derailleur is simple in structure and prevails on the current market. However, the chain and sprockets are vulnerable to damage from external forces and speed changes may be rough and uncertain. Moreover, the chain may come off or even break. The rear transmission hub is compact in size and the mechanical efficiency is high. Gear shifts are
stable and smooth even when the bicycle stops. Rear transmission hubs also have a longer working life and possess many favorable characteristics. [2] Rear transmission hubs have become the focus of research for many international bicycle manufacturers and other research workers. Most of the patents and existing products for rear transmission hubs are held by bicycle companies in Germany, England, and Japan. In 1996, Sachs proposed a basic planetary gear train as the differential unit connected with two sets of 2-stage compound planetary gear trains and one set of 3-stage compound planetary gear train to form a 12-speed rear transmission hub. [3] This was a breakthrough with respect to an increase in the number of forward gears, and the total gear ratio could reach 339%. In 2001, Sturmey-Archer Company combined three sets of basic planetary gear trains to make an eight-speed rear transmission hub, [4] the total gear ratio of which reaches 305%. In 2008, Hsu and Wen [5] designed a 16-speed rear transmission hub with well-distributed SRs between the lowest and highest gears and effectively reduced the burden on the rider. In 2009, Rickels [6] used parallel-connected planetary gear sets to realize a multi-speed rear transmission hub. They installed one-way clutches between the carrier and the ring gear of the planetary gear set so that the activation of each planetary gear set could be controlled. In 2011, Shimano Company designed a transmission hub [7] that could provide 11 forward gears and the total gear ratio reached 405%. In 2011, Hsieh and Chen [8] presented a systematic design process for the implementation of bicycle rear transmission hubs. Most of the research on bicycle rear transmission hubs is focused on the structural design and kinematic analysis of planetary gear mechanisms. [9–17] The distributed-flow type planetary gear mechanism [15] is suitable for multi-speed transmission hubs with a high total gear ratio. The input power from the sprocket splits into two sets of planetary gear trains with different SRs. Then, the power converges on the differential unit and finally transmits to the rear hub shell. The gear-shifting mechanisms have also received considerable attention during these years. In 2013, Chen et al. [2] designed a translational-type gear-shifting mechanism used in a distributed-flow type planetary gear mechanism with eight forward gears. However, the translational-type gear-shifting mechanism occupies a lot of axial space, making them too long to provide more than five forward gears. Also in 2013, Wu and Ren [18] proposed a distributed-flow type planetary gear mechanism with 16 forward gears, but they did not offer any practical and feasible control mechanism for gear shifting.

Although distributed-flow type transmission hubs can offer several forward gears, the design of a practical gear-shifting mechanism is rare. This paper presents the design of an eight-speed rear transmission hub with a novel gear-shifting mechanism to control the gear stage. The topological structure, mechanical components, and working principle of the rear transmission hub are explained. The design process of the cam-type gear-shifting mechanism is elucidated and the embodiment design of a complete eight-speed rear transmission hub, which integrates a gear mechanism with a gear-shifting mechanism, is presented. A prototype was made by 3D printing, to verify the correctness and feasibility of the presented rear transmission hub for bicycles.

2. A planetary gear mechanism

A distributed-flow type planetary gear mechanism presented by Wu and Lin [11] served as a basis for the new developed transmission hub. After removing one set of basic planetary gear train from the original design, the remaining parts are used as the main body of an eight-speed rear transmission hub. This planetary gear mechanism consists of two transmission units (transmission units I and II) and a differential unit (differential unit III). Although the kinematic structure of the planetary gear train is complicated, each mechanical unit has its own function. Two transmission units are used for providing eight SRs, and a differential unit is used for increasing the SR range. A schematic diagram of the presented rear transmission hub is shown in Figure 1. The degrees-of-freedom (DOF) of the planetary gear mechanism can be calculated based on Gruebler’s equation:

$$\text{DOF} = 3(N - 1) - 2I_R - 1I_G$$

$$= 3(13 - 1) - 2 \times 12 - 1 \times 8 = 4$$ (1)

This planetary gear mechanism has 13 links (N), 12 turning pairs (JR), and 8 gear pairs (IG), the DOF of this mechanism is 4. Therefore, four independent constraints must be provided to generate a constrained output motion. Since carrier 5 is connected to the sprocket to provide with one constraint, another three constraints are realized by the engagement of three mechanical clutches. These three constraints can be generated by controlling one-way rotating clutches A, B, C, and fixed clutches Cf1, Cf2, and Cf3, to make the transmission hub outputs an accurate and predictable constrained motion. The distributed-flow type rear transmission hub shown in Figure 1 at most provides eight forward gears, and the related clutching sequence table is listed in Table 1. The first gear (G-1) of this transmission hub is a low speed gear. The second gear (G-2) is a direct drive gear. Gears G-3, G-4, G-5, G-6, G-7, and G-8 are high speed gears. By referring to existing designs of bicycles’ rear transmission hubs, the SR, which is defined as the input shaft angular velocity to the output shaft angular velocity, of each gear stage for the presented planetary gear mechanism is listed in Table 2. Based on these SR
values, the number of gear-teeth for all gear elements can be synthesized by employing the synthesis process.[18]

3. Components of a cam-type gear-shifting mechanism

3.1. Gear-shifting mechanism

For a transmission hub, the SR at each gear stage is realized by simultaneously assigning three coaxial links as the input link, output link, and fixed link. The function of a gear-shifting mechanism is to properly control coaxial links of a planetary gear mechanism. The gear-shifting mechanism within an internal transmission hub employs mechanical components to control one-way rotating clutches and fixed clutches. A gear-shifting mechanism mainly consists of two units; one is the governor unit and the other the connector unit. The function of the governor unit is to engage or release adjacent mechanical members of the gear-shifting mechanism when gears are shifted. The connector unit includes several one-way rotating clutches and fixed clutches, the function of which is the connection of sun gears to the main shaft or the connection of two coaxial links for transmitting power. A functional structure diagram of the gear-shifting mechanism for the transmission hub is shown in Figure 2.

3.2. Components and actuation of a cam-type gear-shifting mechanism

The operation of gear-shifting mechanisms within transmission hubs can be classified as translational type and rotary type for controlling mechanical clutches. The translational type makes use of grooves and sliding blocks on the stationary main shaft to shift gear. This kind of gear-shifting mechanism, however, requires a considerable amount of axial space, which makes it unsuitable for a transmission hub with more than five gears. A rotary type gear-shifting mechanism reduces the amount of axial space needed, so it is used in rear transmission hubs that offer more than eight gears. However, the topological structure of rotary type gear-shifting mechanisms are complicated, difficult to manufacture and also expensive. In this study, we use cams to control the engagement of

Table 1. Clutching sequence table of the presented rear transmission hub.

| Gears | Rotating clutches | Mechanical clutches | Fixed clutches |
|-------|-------------------|---------------------|--------------|
|       | A     | B     | C     | CF1   | CF2   | CF3   |
| G-1   |       | ●     | ●     | ●     | ●     |
| G-2   |       | ●     | ●     | ●     | ●     |
| G-3   |       | ●     | ●     | ●     | ●     |
| G-4   |       | ●     | ●     | ●     | ●     |
| G-5   |       | ●     | ●     | ●     | ●     |
| G-6   |       | ●     | ●     | ●     | ●     |
| G-7   |       | ●     | ●     | ●     | ●     |
| G-8   |       | ●     | ●     | ●     | ●     |

Table 2. The SR of each gear stage for the presented planetary gear mechanism.

| Gear | G-1 | G-2 | G-3 | G-4 |
|------|-----|-----|-----|-----|
| Speed ratio value | 1.184 | 1.000 | 0.867 | 0.764 |
| Gear | G-5 | G-6 | G-7 | G-8 |
| Speed ratio value | 0.684 | 0.618 | 0.528 | 0.488 |
feasible and reasonable. This section presents a design process, as shown in Figure 5, for the embodiment design of cam-type gear-shifting mechanisms. The design steps are listed as follows:

4.1. Step 1. Choose a planetary gear mechanism

A distributed-flow type planetary gear mechanism shown in Figure 1 is chosen as the main body of the rear transmission hub for bicycles. The input power from the sprocket is transmitted into the gear mechanism through carrier 5, and the output power is transmitted from ring gear 8 to the hub shell.

4.2. Step 2. Calculate the DOF of the planetary gear mechanism

From Equation (1), we can see that the DOF of this gear mechanism is 4, four constraints are required to manipulate this gear mechanism. Carrier 5 connected to the sprocket provides an input constraint. Another three constraints must be provided by the actuation of rotating and fixed clutches. That is the reason why three mechanical clutches are simultaneously engaged at each gear stage shown in Table 1.

4.3. Step 3. Determine the clutches that need to be controlled by the gear-shifting mechanism

Since one-way rotating clutches A, B, and C are automatically engaged based on the relative angular velocity of the
To check the feasibility of the presented gear-shifting mechanism, commercial FEA software is applied to analyze the stress distribution on the cam lever and pawl blocks. Based on the simulation results, the maximum stress is 14.04 MPa and the maximum strain is 0.0106. Because the yield strength of the medium-carbon steel is 343–490 MPa, the maximum stress on the gear-shifting element is lower than the yield strength of steel.

pawl and the ratchet, they do not need to be controlled by the gear-shifting mechanism. The clutches that must have further control by the gear-shifting mechanism are fixed clutches Cf1, Cf2, and Cf3, as shown in Figure 6.

4.4. Step 4. List the clutching sequence table

The related clutching sequence table of this rear transmission hub is shown in Table 1. It is interesting to find that three fixed clutches do not need to be controlled at gear stage G-2, which is a direct drive gear.

4.5. Step 5. Plot annular schematic diagrams

A cam-type gear-shifting mechanism is used for this eight-speed rear transmission hub. We use an annular schematic diagram to represent the activation of fixed clutches Cf1, Cf2, and Cf3. Since there are eight forward gears, each annular schematic diagram is divided into eight equal parts and each sector part represents one gear stage. As can be seen in Figure 7, the colored segment indicates the related fixed clutch is engaged at this gear stage, while the uncolored segment represents the fixed clutch is unengaged.

4.6. Step 6. Embodiment design of cam-type gear-shifting mechanisms

Each colored segment on the annular schematic diagram represents a flat surface on the circumference of the cam lever as shown in Figure 8. The configuration of the cam lever is shown in Figure 9. Figure 10 shows an exploded view of the cam-type gear-shifting mechanism. The cam-type gear-shifting mechanism, which governs the gear stage of the rear transmission hub of a bicycle, is manipulated by the cyclist through a lever-actuated shifting device installed on the bicycle’s handlebar.

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research and development of gear-shifting mechanisms for rear transmission hubs with more than eight forward gears.

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**Figure 11.** Exploded view of an eight-speed rear transmission hub for bicycles.

**Figure 12.** A 3-D printed prototype of the developed eight-speed rear transmission hub.

Therefore, the strength of the gear-shifting mechanism is safe.

5. **A new eight-speed rear transmission hub**

The cam-type gear-shifting mechanism developed in Section 4 is further integrated with the distributed-flow type planetary gear mechanism shown in Figure 1 to form a new eight-speed rear transmission hub for bicycles. An exploded view of the transmission hub is shown in Figure 11 and a prototype, prepared by 3D printing, is shown in Figure 12.

6. **Conclusion**

This paper offers a design process for the development of multi-speed rear transmission hub with a cam-type gear-shifting mechanism. A new eight-speed rear transmission hub is presented based on the design process. This design process can also be promoted for further
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