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EFFECTS OF THE ANGULAR VELOCITY OF A FLYWHEEL ON THE GYROSCOPIC STABILIZATION OF A BICYCLE

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Abstract: *Learning to ride a bicycle requires simultaneous development of various motoric and perceptual capabilities. During the learning process, training wheels are often used both as a training device and as a safety measure. Gyroscopic stabilization offers an alternative way for balancing the bicycle, enabling the possibility to control the amount of the assistive balancing force for more efficient learning. In this study, the effects of a gyroscope's flywheel velocity were observed on a small-sized bicycle. To measure the stabilizing effect, a bicycle was fitted with a control moment gyroscope and an inertial measurement unit. The resulting stabilizing forces were measured to show the correspondence between the stabilizing effect and the flywheel velocity.*

Key words: gyroscope, stability, learning, training

1. INTRODUCTION

Cycling is a great way to get daily exercise and an environmentally friendly way of transport. In many cities cycling is one of the fastest ways to get around. Cycling is also a very competitive sport. The main thing needed for cycling is the skill to balance the bike even at low speeds.

Children are often taught how to ride a bicycle when they are between ages of 3 and 8 years old, averaging just over 5 [1, 2]. Some children take to it naturally, others do not. Every child has a different physical and mental development. This can easily lead to frustration if siblings or other children learn faster. While learning how to ride a bicycle, kids are a risk to themselves and others in traffic.

The earliest sketches of a bicycle are said to be from 1493 by Leonardo da Vinci's pupil, Gian Giacomo Caprotti. The bicycle was later invented in the early 19th century. The first vehicle that was powered by a human and had only two wheels was the German Draisine dating back to 1817 by Karl von Drais. The bicycle has evolved quite a lot over the years. There were also trends of multiple wheels, big wheel on the front or no pedals at all. Nowadays the basic structure of a bike has been standardized. [3]

The goal of this study is to help children to learn how to ride a bicycle by designing a device that can be attached to a bicycle and self-stabilizes it. In this study the optimization of the balancing control system in the bicycle is peripheral to measuring the forces generated with the device. The main focus is on the self-stabilization and the training aspect is secondary.

There's a saying, "It's as easy as riding a bike". In the mathematical world, it definitely is not so. A bicycle has an intricate geometry and it has many degrees of freedom. Thus creating a comprehensive and accurate model of a bicycle is complicated. This is definitely a particular challenge when trying to design the stability control for a bicycle. This study simplified the situation by focusing only on the torque needed for stabilizing the bicycle in an upright position.

This article is structured as follows. First we introduce the methods that are used for stabilizing a bike. In this section the calculations, simulations and prototyping are showed and explained. The next part relates the results from the tests. The last part of the article is discussion concerning the project's success and thoughts about future plans.

2. METHODS

Lam, Yetkin and Ozguner have successfully constructed small bicycles that can autonomously stabilize themselves so that they stand upright [4, 5]. These bicycles were based on a control moment gyroscope (CMG) which consists of a flywheel spinning at an even speed and a gimbal that is used for rotating the spinning flywheel around the vertical axis. Rotating the spinning flywheel moderately around the vertical axis causes a moment that can be utilized for balancing the vehicle.

In this study a CMG was used for stabilizing a bicycle. The gimbal was attached to a child-size bicycle as show in Figure 1. The original frame was marginally lengthened to fit the CMG.

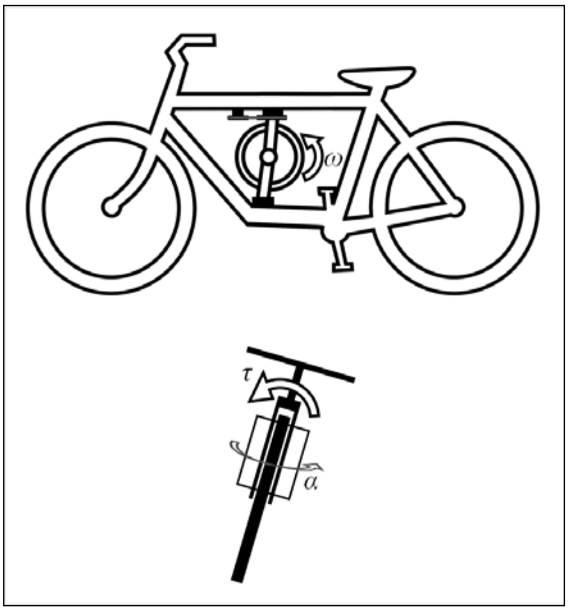

Fig. 1. Representation of the CMG attached to the bicycle.

The flywheel was driven using a pneumatic motor attached to the gimbal of the CMG. At first a DC-motor was used instead but the small pneumatic motor was more suitable for frequent testing. Accelerating the flywheel using the pneumatic motor was more practical and there was no risk of overloading the motor. The shaft of the flywheel was connected to the output shaft of the motor via a belt drive. The rotation around the vertical axis was achieved using a servomotor via a belt drive. The gear ratio in both belt drives was 1:1.

The mass and the inertial moment of the flywheel were optimized to the need. On the one hand the structure was to be as light as possible. At the same time the shape of the flywheel had to be designed for maximal inertial moment. Thus the mass of the flywheel concentrates on the perimeter.

As a safety measure the frame of the CMG was constructed using flat bar iron. The result was a sturdy casing that would hold the flywheel inside even if something would go wrong. Bearings were fitted to both ends of the shaft of the flywheel. The frame was supported by a bearing from the top and from the bottom so that it could be rotated around the vertical axis.

The tilt angle of the bicycle was measured using an inertial measurement unit (IMU) which is capable of measuring 6 degrees of freedom. The whole system was controlled using a microcontroller. When stabilizing the bicycle the angle of the flywheel was controlled based on the tilt angle of the bicycle. The system was powered by a lithium polymer battery.

The principle of using a CMG was first tested using Adams and Simulink simulations. The Adams simulations verified that both the system and the stabilizing phenomenon worked as expected. The simulations gave some advice for the magnitude of the parameters in the actual structure.

Simulink simulations were made to verify the results from Adams simulations. These simulations are based on the basic physics formula for torque. The formula is

$$\boldsymbol{\tau} = \mathbf{I} \times \boldsymbol{\alpha} \qquad (1)$$

where $\mathbf{I}$ is the inertia of the object, $\boldsymbol{\alpha}$ is the acceleration and $\boldsymbol{\tau}$ is the torque produced. This formula can be used to calculate the torque generated by a gyroscope. The formula is then added with the speed $\boldsymbol{\omega}$ and the inertia $\mathbf{I}$ of the flywheel.

$$\boldsymbol{\tau} = \mathbf{I} \times \boldsymbol{\alpha} + \boldsymbol{\omega} \times \mathbf{I} \times \boldsymbol{\omega} \qquad (2)$$

The formula is simplified because the speed of the flywheel is perpendicular to the acceleration off the gimbal motor. Then the formula takes the following form:

$$\boldsymbol{\tau} = \mathbf{I}(\boldsymbol{\alpha} + \boldsymbol{\omega}^{2}) \qquad (3)$$

This formula is then used to run the simulations to estimate the final technical specifications. In addition to the simulations, the 3D-models created with Creo 2.0 were relevant for adjusting the dimensions of the structure. The final technical properties (Table 1) were based on the computer models.

Rotational speed of the flywheel	7,000 rpm (max)
Mass of the flywheel	7 kg
Flywheel’s moment of inertia	0.059 kg*m^2
Material of the flywheel	steel
Range of the IMU	±16g and ±2000°/s

Table 1. The technical specifications.

The purpose of the study was to measure the useful torque created with the CMG. In order to remove one degree of freedom the rotation of the handle bars and the front wheel was prevented.

The torque generated with the CMG was measured at different angular speeds of the flywheel. The speed of the flywheel was monitored with a laser tachometer. The rotation around the vertical axis was executed by running the servomotor from one side to the other in the same way in each test. As mentioned later in the Results chapter the servo was not able to rotate the CMG at a similar rate at all flywheel speeds.

In the test setup the bicycle was virtually in an upright position though just leaning to one side. The bicycle was held in place by a force gauge attached to a wall from the other end. The initial situation was set as the neutral point where the force value was tared to zero. As the CMG was rotated around the vertical axis, the generated torque made the bicycle pull the force gauge. The bicycle staid in the initial position as the force gauge did not allow it to tilt. The force reading from the gauge was stored. The generated torque was calculated by multiplying the force with the vertical distance of the force gauge compared to ground. Measurements were carried out with the setup presented in Figure 2.

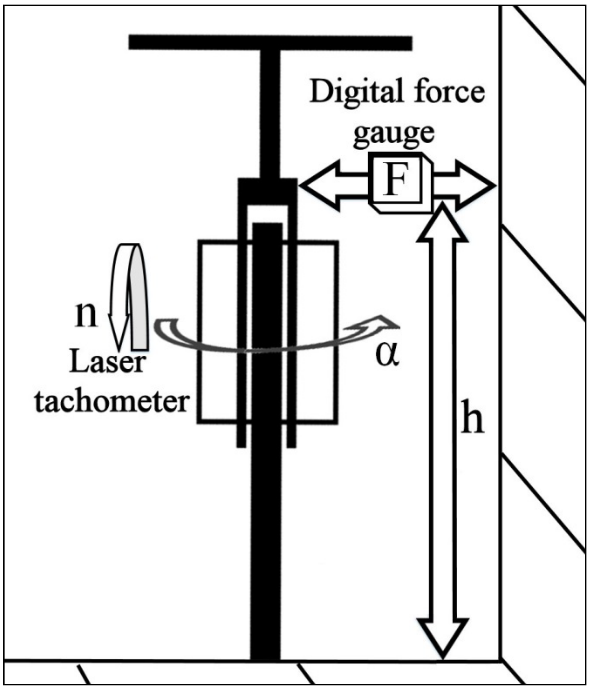

Fig. 2. Experimental setup where the CMG is attached to the frame of a bicycle. The generated force (F) at height (h) is measured as the CMG is rotated around the vertical axis. The force gauge is attached to the bicycle from one end and to the wall from the other.

3. RESULTS

Figure 3 presents the measured dependency between the rotational speed of the flywheel and the torque generated with the CMG.

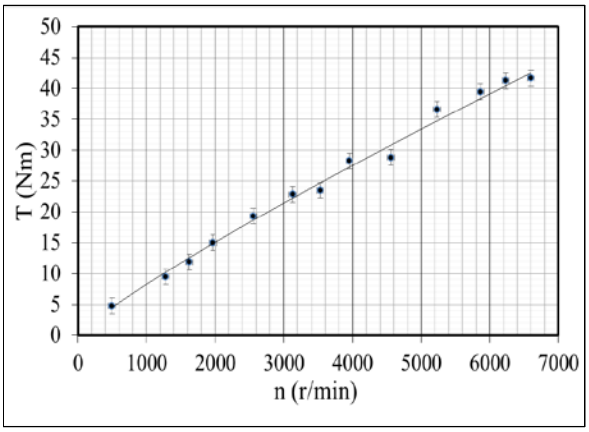

Fig. 3. Experimental results of the gyroscopic torque generated as a function of the rotational speed of the flywheel.

During the tests it was clearly visible that the servo motor was not able to perform the rotation around the vertical axle equally fast at all flywheel speeds. As the speed of the flywheel was increased the rate at which the CMG turned was reduced. The servo motor did not have the capability to maintain the same rotational speed as the torque of the flywheel increased with the speed.

Since the servo was not capable of rotating the flywheel at a similar rate at all speeds the ascending speed-torque curve in figure 3 gradually becomes less steep. The torque should grow exponentially because the angular speed vector is to the power of two in the presented formula (3).

The maximum torque was generated at the highest used flywheel speed. As the flywheel was run at the speed of 6600 rpm the generated torque was 41 Nm. The torque needed for bringing a bicycle with a rider back up from a given tilt angle can be calculated using formula (4).

$$\boldsymbol{\tau} = \mathbf{h} \times \mathbf{m} \times \mathbf{g} \times \mathbf{sin}(\boldsymbol{\beta}) \qquad (4)$$

where $\boldsymbol{\tau}$ is the torque needed, $\mathbf{h}$ is the combined centre of gravity, $\mathbf{m}$ is the combined weight of the rider and the bicycle, $\mathbf{g}$ is the standard gravity, and $\boldsymbol{\beta}$ is the tilt angle.

If the combination of a rider and a bicycle ways 35 kg and the combined centre of gravity is located at the height of 0.45 meters 41 Nm is enough to bring the bicycle back to an upright position from the tilt angle of 15 degrees. This would be quite an extreme situation and even not desirable. According to Yetkin [6] it is possible to keep the tilt angle at a maximum of 1 degree with well-tuned control. The same control system can also bring the bicycle back from a tilt angle higher than 1 degree [6]. Taking this is into consideration gives a good perspective to the practical capabilities of the system. 41 Nm is enough to bring back up a combined mass of 100 kg at the height of 0.8 metres from a tilt angle of 3 degrees. Based on this the system could stabilize even adults riding a bicycle.

4. DISCUSSION

For now the study focused on confirming the torque that can be drawn from the CMG. The torque generated is easily enough for stabilizing the combination of a bicycle and a rider. The torque generated can be utilized for stabilizing or assisting riders and bicycles of various sizes. A CMG stabilization system could be used for teaching children to ride a bicycle but also for assisting adults who have difficulties is balancing a bicycle. The group of adults requiring assistance could consist of elderly people and persons who have difficulties because of medical issues.

Within the framework of this study the control system of the CMG was not developed so far that the bicycle would self-stabilize itself for a time span of much more than ten seconds. The bicycle would quickly get unstable and tip to either side.

Based on the study it is quite challenging to fit a control moment gyroscope to a bicycle. Through decades of testing a bicycle is a highly refined vehicle which does not essentially have room for a CMG. In this study the small bicycle frame had to be extended from the middle to fit the CMG. Thus the bicycle was no longer driveable for a child. To power the motor of the flywheel a CMG system requires either a very high capacity battery or a pneumatic compressor which both are difficult to implement to a mobile and light system. The support structure of the CMG was also slightly in the way of pedalling. In addition the CMG system weighs over 20 kg. The weight of the CMG is an enormous problem for the user and especially for a children's bicycle. If the CMG technology is used in the future for learning or other assisting purposes it almost inevitably requires a new frame design for the bicycle and better solutions for storing energy.

5. CONCLUSION

The test system demonstrates how torque can be generated with a CMG for stabilizing a bicycle. A clear dependency between the rotational speed of the flywheel and the torque can be seen in the results. However, the torque attained is not dependent only on the rotational speed of the flywheel. The non-linearity of the angular servomotor was one of the parameters affecting the results.

The test system can next be further developed so that the CMG makes the bicycle truly self-stabilizing even with a rider as a load. Then, gradually decreasing the amount of applied stabilizing assistance according to the improved skills of the cyclist could be beneficial. The system proved to generate enough torque for stabilization purposes. Thus making the system self-stabilizing even when manned is most of all down to refining the control system of the CMG.

The test system cannot be properly used in a bicycle in its present configuration as the bicycle is nearly undrivable. The control system does not yet take intentional tilting during cornering into consideration. The CMG could be made more feasible by reducing the weight of the flywheel and the whole system. The reduced weight of the flywheel could be then compensated by increasing the rotational speed of the flywheel.

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