Exploring the Axial Rigidity and Precession Motion of Gyroscopes and their Application as Mechanical Dampers and Stabilisers

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Abstract

This project embarked on an in-depth exploration of two core characteristics inherent in a gyroscope: first, the rigidity of the spin axis, and second, the motion of precession. These investigations served as a foundation for designing and assembling two innovative devices: a gyro-pendulum that demonstrates damped oscillations, and a self-balancing tumbler equipped with reaction wheels, both designed to showcase potential applications of a gyroscope as a damper and stabilizer.

The creation of the gyro-pendulum commenced with a comprehensive analysis of the dynamics in a generic gyroscope, followed by the application of Lagrangian mechanics to the gyro-pendulum in the scenario of nonconservative torque. A system of dynamic equations was systematically resolved via Python, incorporating parameters akin to those used in the actual design process. The outcomes verified that with the application of nonconservative torque, such as accelerating the flywheel's rotation, the amplitude of nutation oscillation progressively diminishes. Subsequently, using this foundational knowledge, a handheld stabilizing apparatus was designed and partially assembled. This prototype demonstrated a tangible damping effect, thereby affirming the theoretical basis and the results deduced from the simulations.

The self-balancing tumbler leveraged the principle of angular momentum conservation. The spotlight in this segment of the project was motor control. By designing a sophisticated algorithm that analyzed the input from the accelerometer, gyroscope, and Hall effect sensor, the direction and speed of the reaction wheel could be dynamically adjusted, thereby achieving a satisfactory degree of self-balancing.

I. Background

Our project had an initial aim of developing a cost-efficient camera stabilizer, as most commercial options were expensive due to their incorporation of automation and motion-sensing functions. Recognizing that mechanical systems often offer a more affordable solution; we explored various stabilizers in different fields and industries. Eventually, we focused on the concept of gyroscopes, guided by the preconception that spinning objects possess inherent stability under certain conditions.

Drawing inspiration from the behavior of a spinning top, which resists toppling due to the additional torque required to change its angular momentum, we realized that faster spinning leads to increased rigidity along the spinning axis. This observation prompted us to consider a design that could maintain camera balance against external torques resulting from sudden user movements.

We intended to approach this project with the following steps:

1. Research into the existing stabilizer design to gain inspiration for our build, and propose conceptual designs.
2. Research into the mechanical descriptions of gyroscopes and study the mathematical representations.
3. Based on existing models and theories perform computer simulations and numeral calculations for prediction.
4. With the previous results, consolidate the design with specific parameters, and source materials and parts.
5. Construct the device.

According to our progress, we extended our project with the following additional steps:

1. Research into the gyro-pendulum setup in terms of Lagrangian mechanics to better describe the later designs.

2. Computer calculations on math models of gyro-pendulum
3. Exploring the precession motion of gyroscopes and its use as a stabilizer when combined with accelerometer.
4. Building gyro-driven tumbler according to existing design to demonstrate the previous point.

II. Description of Project Work

Week 1-2 (Initial Ideas, Research and Designs)

- Initial contact was achieved at the end of the second term, and we came up with a broad idea of a mechanical stabiliser and in a meet at the start of the 3rd term we furthered this topic to resolve the instability of handheld camera device due to shaky hands of the user. Then, as a group we investigated the stabilisers of boats, buoys, airplanes, robots, and market researched into the existing camera stabilisers, e.g., camera gimbal sets of Steadicam and found out they are expensive, and we, therefore, considered to aim for a cost-efficient design. We created a shared document for the collection of this information.
- Based on the gathered information DK proposed an initial conceptual sketch of a gyroscope directly mounting on a binocular, and we met to discuss the details, including the shape of flywheel, how to drive the flywheel, and estimated the dimensions and parameters. And during this period, we connected with supervisor, discussed the practicality of using a gyroscope as stabilisers, and potential setup and materials.

Week 2-3 (Further Designs and Preliminary Theory and Simulations)

- DK consulted a Physicist confirming the stability of spinning objects exits and we further researched into gyroscope theories and hypothesized the concept of gyroscope axial rigidity based on the primary research in the airplane gyrocompasses. DK and ZM worked on improving the current design, and sourcing relevant materials and parts.
- Based on the previous research JJ hypothesized the concept of rigidity and proposed a preliminary quantitative description.
- YY gained inspiration from a textbook of a gyroscopic design with gimbal sets and proposed the second design and produced a modelled CAD using Rhino 7.
- YY and JJ read into lecture notes of a aero engineering Dynamics course and proposed more specific theory, YY set out to code the dynamical relations in the notes in Python and by incorporating a numerical ODE solver program, managed to plot the response of the angular displacement of the spin axis of the flywheel and, and JJ extended the code to a set of parameters plotted and demonstrated the rigidity of a spinning flywheel.

Week 4-5 (Practical's material sourcing and Further theory)

- In the fourth week, we reviewed the latest design, and thought of its impracticalities for some assumptions involved, including frictions in multiple joints that causes unavoidable initial precession motion. Therefore, we spend this week revising our research accompanied by daily meetings, discussing possible alternative approaches.
- On 26 May, based on the new requirements and the previous ideas, DK proposed another conceptual design with the attempt to overcome the previous pitfalls. The new design attempts to hang the subject camera below the spinning flywheel like a gyro-pendulum. As a group, in consecutive four meetings, we focused on improving the new design and determined the parameters and dimensions of each bit, after which, ZM sourced the relevant materials and YY transferred the drawing design into a 3D model in separate parts ready for 3D printing.
- While YY looked further into the theories of Lagrangian mechanics studying the Gyro-pendulum, ZM started researching and designing of accelerometer that was to be installed on the device aimed to supply the device with an active response mechanism against external torque.

Week 6-7 (Building the prototype)

- While YY continue to compile relevant research, the rest started with the construction of the device after JJ finished the document on risk assessments and got approval signature from supervisor.
- When we first assemble the part, due to the inconsistent joint connections and innate unbalance of the structures, the whole device wobbles on activation and during consistent spin. We attempted to balance the misalignment by attaching additional weights onto the flywheel with blue tags but was not effective. DK proposed attaching symmetrical rings the size of the flywheel to adjust the moment of inertia to fix the misalignment and attempted to reduce the wobble and was to a large extent successful.

- Because of the structural weakness of plastics we printed, we abandoned some of the parts that were supposed to be attached and finalised the device as a primitive gyro-pendulum.
- Meanwhile, ZM designed the circuit system on an Arduino board incorporating 3-axis accelerometer to be connected to the gyro-pendulum motor to achieve automated feedback and counteraction.
- After completing the research YY started a parallel construction of a self-balancing gyro according to an existing design aimed to further demonstrate gyro balancing with additional motors and Arduino board and worked on the motor control circuit.
- In the final phase, DK worked on the poster design and drawing and JJ this document.

III. Summary of Results

The dynamic equations of a simple gyro are numerically solved using computer with parameter inputs similar to those in the design and obtained angular displacement response of the spin axis, demonstrating the fundamental idea of spin axis rigidity of a flywheel. Other solutions to dynamic equations of the gyro-pendulum were also obtained and it showed diminishing amplitude of oscillations of a rigid pendulum with a spinning gyro attached at the end as expected. Our latest design of gyro-pendulum was partially constructed with a functioning motor-flywheel system capable of safely operating with a spin rate around 200 rpm, granting the whole system stability after certain number oscillations with decaying amplitude, as predicted by computer simulations. The attempt to incorporate the accelerometer to the motor to achieve automated real-time disturbance cancellation was successful. Moreover, the attempt to construct a self-balancing gyro was incomplete yet partially successful, with a working support frame and automated motor control system, and further tuning of the program are need.

IV. Conclusion

Generally, our constructions are successful. Measurements from our prototype are consistent with the computer numerical estimations using existing models. Hence we conclude these results have validated our understanding and approach to the application of gyroscopes as dampers and stabilizers.

Unfortunately, the design was mainly troubled by the wobble of the flywheel due to the asymmetry of the rotation about the axial shaft and the friction in the bearing connection, such that we could not have further attachments, e.g., having /connected mounting platform. This is either because of the misalignments of the components or the uneven distribution of mass of the flywheel. Hence, we proposed to design the flywheel as a stacked assembly of multiple identical short cylinders, such that, by manually adjusting the relative positions of the rings, we could manage to balance the weight and achieve better symmetry in the moment of inertia of the system.

V. Purchases, Existing Items and Use of 3D-Printing

A. Borrowed from Lab

Motor: MFA/Como Drills 970D Series Single Ratio Gearbox (4.5 – 15V DC)

DC Power Supply: TTi EL302R Power supply (30V 2A)

Super Glue: RS Pro Super Glue (Cyanoacrylate)

Electric Board: Arduino Uno Rev3

B. Items Purchased

DC Power Supply: TTi EL302R Power supply (30V 2A)

Aluminium Rod

- Supplier/Source: Aluminium Online
- Specifications: 15mm Aluminium Round Bar (Length: 500 mm)
- Price: 4.90 GBP

Ball Bearing (Thick)

- Supplier/Source: RS PRO
- Specifications: RS PRO Deep Groove Ball Bearing - Sealed End Type, 15mm I.D, 35mm O.D
- Price: 2.37 GBP

Ball Bearing (Thin)

- Supplier/Source: Bearing Shop UK
- Specifications: 61702-2RS (Also known as 6702-2RS)
- Price: 4.10 GBP
- Number purchased: 5

Ball Joint 1

- Supplier/Source: Autosport Bearings & Components
- Specifications: IKO GE15GS2RS SEALED SPHERICAL PLAIN BEARING, GE15GS2RS
- Price: 9.71 GBP
- Number purchased: 1

Ball Joint 2

- Supplier/Source: Ganter Norm
- Specifications: GN 648.8 Ball Joints
- Price: 9.70 GBP

- Number purchased: 2

Nylon Rope

- Supplier/Source: Amazon
- Specifications: Yucong 2/4/6/8/10MM 30M (98ft) Satin Nylon Trim Cord, Rattail Silk Cord
- Price: 11.99 GBP

Accelerometer

- Supplier/Source: Amazon
- Specifications: MPU-6050 MPU6050 6-axis Accelerometer Gyroscope Sensor
- Price: 14.99 GBP

Motor Controller

- Supplier/Source: Amazon
- Specifications: DAOKAI 10 Pcs L293D Stepper Motor Drivers Controller
- Price: 5.89 GBP

C. Materials produced with CNC and 3D Printer

Cap support + Weight holder: CNC aluminium single sided

Structural support: CNC aluminium double sided

Isolation handle: 3D print

Motor system: 3D print PLA

1kg Flywheel: CNC aluminium single side

Platform support and platform: D print PLA

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