ME2206: Kinematics and Dynamics of Machinery: Spring 2022

Simscape Multibody Project Final submission: Report

Group number: 01

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Title: Gyroscope

Aim:

- To qualitatively observe and understand the fundamental principles of working of Gyroscope (rigidity and precession).
- To visually understand the non-intuitive Gyroscopic couple.
- To verify the dependence of Gyroscopic couple, spin angular velocity ω_s and precession angular velocity ω_p.
- To understand the working principle of some of the primary applications of the gyroscopic effect

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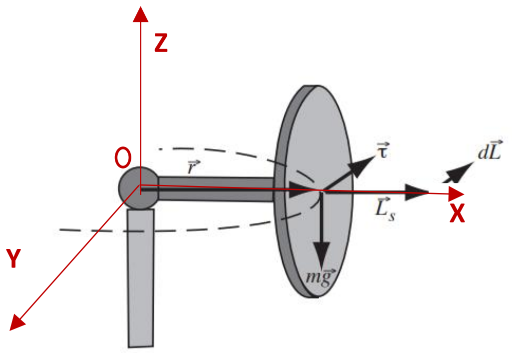
Gyroscope: In its most basic form, a gyroscope is a wheel or disc mounted on a gimbal to spin rapidly around an axis that is free to change its direction.



A disc attached to a spindle (spin axis) is given alongside, mounted on a rotating frame.

Case 1: When the disc is not given any spin

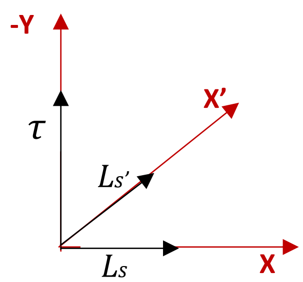
Due to the weight of the disc, the system experiences a torque $\tau = mgr$, due to which the disc oscillates about point O and finally comes to rest.

Case 2: When the disc is given an angular velocity ω_s about X-axis, we expect the disc to rotate in that direction. However, in reality, along with the rotating disc, the spin axis of the disc precesses with an angular velocity ω_p. This gravity-defying effect of the Gyroscope is called precession.

Why does precession Occur?

Rotational analogous of Newton's second Law,

$$\vec{\tau} = \frac{d\vec{L}}{dt}$$



As the disc rotates under the influence of torque due to self-weight, the spin angular momentum vector changes its direction, i.e., the spin angular momentum vector follows the direction of torque due to self-weight, as a result of which the system precesses. A change in angular momentum induces a torque called the active gyroscopic couple.

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This is visually represented in our model Gyro_selfweight.slx

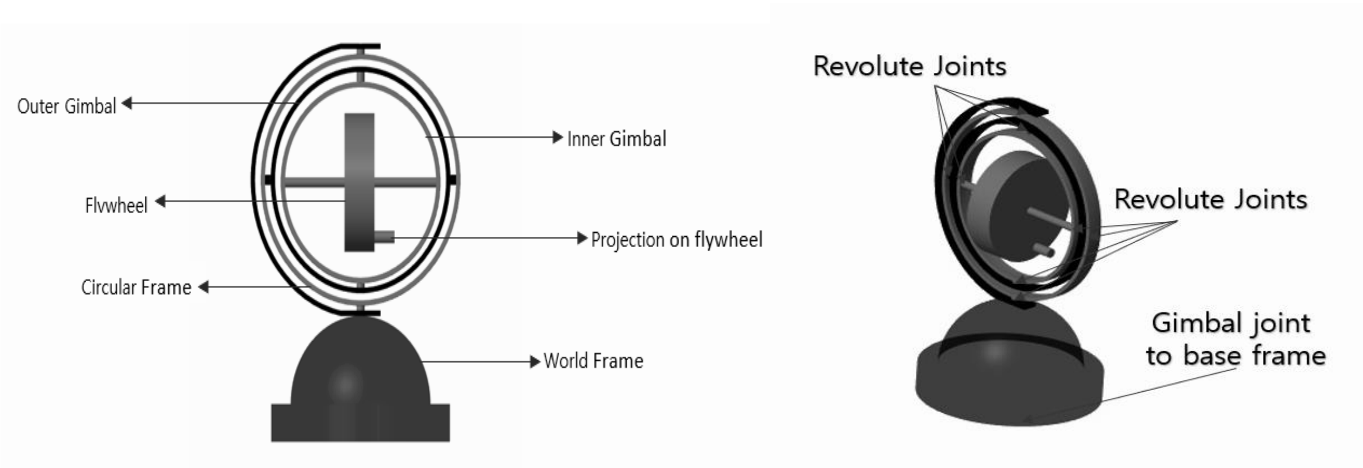
Assumptions made:

- The bearing is assumed to be frictionless.
- No other external forces are acting on the system except the weight of the disc.
- The mass of the spin axis is small compared to the mass of the spinning disc, and hence torque due to its weight is neglected.
- The dimensions of the spin axis are tiny, and hence its value is also neglected in the mass moment of inertia calculations.
- The spin angular momentum L_s is constant, and hence the total mechanical energy, including gravitational potential energy, must also be of a constant value.

The fundamental principles of Gyroscopic action

Description:

This 3 DOF Gyroscope consists of a flywheel mounted inside an inner gimbal, which is mounted inside an outer gimbal. The entire structure is supported by a circular frame free to rotate about its vertical axis of symmetry within the world frame. Although all the gimbals and the frames are free to rotate, we can also fix some of these from moving. The flywheel also has a small external projection that helps us clearly view and understand the direction of spin.



3 DOF Gyroscope

Modelling Process:

- Firstly, all parts were modelled using 3D CAD software (Fusion360 and Solidworks). Then they were imported to Simscape multibody as file solids wherein all parts were meshed/mated using necessary joints. We have not used rigid transform blocks as the frames are correctly aligned internally.
- Revolute joints are used to connect the following
  - ✓ The frame to the outer gimbal
  - ✓ The outer gimbals to inner gimbals
  - ✓ The innermost gimbal to the flywheel

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- In the case of Gyro_rigidity.slx, the frame is attached to the world reference frame through a gimbal joint.

Kinematics:

A gyroscope mounted in three gimbals has three degrees of freedom:

- The spin axis: Axis perpendicular to the plane of the flywheel
- The tilt axis: Horizontal Axis perpendicular to the spin axis
- The veer axis: Vertical axis perpendicular to both spin and tilt axis

Rigidity in Space:

- Rigidity in space describes the principle that a gyroscope remains in the fixed position on the plane in which it is spinning, unaffected by any external forces and torques, including Earth's rotation. Resistance to change in the direction of rotation of the flywheel is rigidity.
- If the flywheel has a high mass moment of inertia, it will have a greater rigidity, i.e., the spin axis maintains alignment to a fixed point in space.
- Therefore, a greater flywheel mass and a greater spin angular velocity stabilise the spin axis' alignment.
- Some applications of Rigidity: Gyrocompass, Artificial Horizon
- Gyro_rigidity.slx gives a visual representation of this phenomenon.
- Please set the following conditions to observe rigidity:
  - ✓ Set the velocity target of revolute joint3 to 1 rad/s
  - ✓ Set ty input for the gimbal should be 0.05 N-m.

Precession:

- Tilting or turning of a gyro in response to a deflective force is called precession.
- The reaction to this force does not occur at the point at which it was applied; instead, it occurs at a point 90° later in the direction of rotation. The amount of precession experienced is directly proportional to the strength of deflective force and inversely proportional to the mass moment of inertia and angular spin velocity.
- Precession and rigidity are complementary phenomena.
- Some applications of Rigidity: Torpedo Steering Mechanism, Turn and slip indicators
- Gyro_precession.slx gives a visual representation of this phenomenon.
- Please set the following conditions to observe precession:
  - ✓ Provide a torque of around 1 to 2 N-m to revolute joint2
  - ✓ Let the velocity of the flywheel be low ~0.5 rad/s

The non-intuitive Gyroscopic Couple

Gyroscopic Effect can be observed even in the absence of any medium, i.e., vacuum. The introduction explained how a spinning disc, due to its self-weight under the action of an active gyroscopic couple, precesses in the horizontal plane. The following model and analysis explain the action of a gyroscopic couple in a vacuum.

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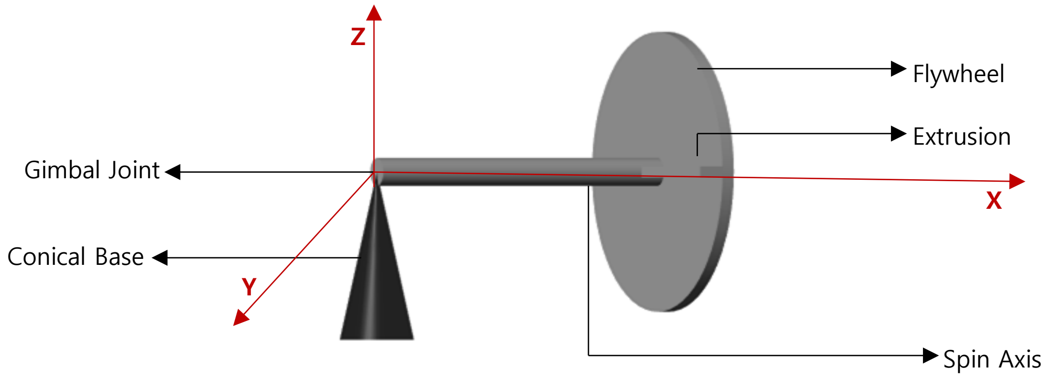
Description:

A flywheel free to rotate about an axis perpendicular to its plane is mounted on a conical base at its tip in space (vacuum). The joint at the tip is assumed to be a gimbal joint (3 DOF). The flywheel has an extrusion that helps us clearly view and understand the direction of spin.



Gyroscopic Action in Vacuum

Modelling Process:

- Firstly, all parts were modelled using 3D CAD software (Fusion360 and Solidworks). Then they were imported to Simscape multibody as file solids wherein all parts were meshed/mated using necessary joints. We have not used rigid transform blocks as the frames are correctly aligned internally.
- A gimbal joint is used to connect the conical base to the centre of the spin axis of the flywheel

Kinematics and Mechanism:

When a spinning flywheel is also given a torque along Z-axis, the body precesses. The spin angular momentum vector follows the direction of torque, and this change in angular momentum results in an active gyroscopic couple. From Newton's Third Law, every action has an equal and opposite reaction. The reactive couple oriented opposite to the active couple causes precession.

This is visually represented in our model Gyrowheel.slx

Observations:

- Case 1:
  - ✓ ty = 1 N-m
  - ✓ tz = 0 N-m
  - ✓ The disc spins about its spin axis
- Case 2:
  - ✓ ty = 0 N-m
  - ✓ tz = 1 N-m
  - ✓ The spin axis rotates about Z - axis
- Case 3:
  - ✓ ty = 1 N-m

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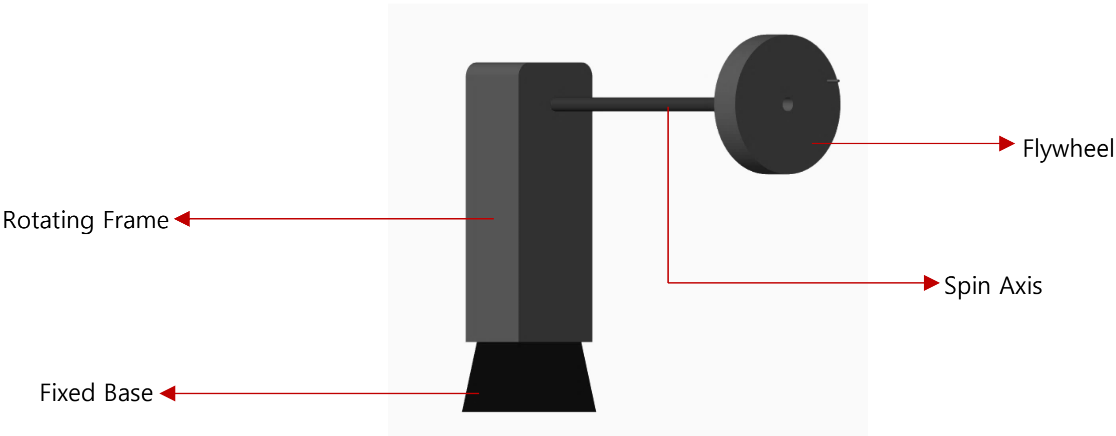
- ✓ t_z = 1 N-m
- ✓ We expect a superposition of the first and second cases; however, this does not happen. The disc also experiences a gyroscopic couple due to which it rotates, as seen in the simulation.

Dependence of Gyroscopic couple, spin angular velocity ω_s and precession angular velocity ω_p

Description:

Considering the same model used in the introduction, i.e., a disc attached to a spindle (spin axis) mounted on a rotating frame, we have verified the dependence of Gyroscopic couple, spin angular velocity ω_s and precession angular velocity ω_p.

This is visually represented in our model Gyro_selfweight.slx



Gyroscopic Action due to self-weight

Modelling Process:

- Firstly, all parts were modelled using 3D CAD software (Fusion360 and Solidworks). Then they were imported to Simscape multibody as file solids wherein all parts were meshed/mated using necessary joints. We have not used any rigid transform blocks as the frames are properly aligned internally.
- Revolute joints are used to connect the following
  - ✓ Fixed Base to the Rotating Frame
  - ✓ The flywheel to the spin axis

Analysis:

- For three different lengths of the spin axis and two masses of the flywheel, for a given set of ω_s values, ω_p values were noted down as shown in the display. The recorded data is in the table below.
- From the tabulated values, we can conclude that
  - ✓ For a fixed mass of flywheel and fixed axis length, ω_p values decrease with an increase in ω_s values.
  - ✓ As the torque increases (due to an increase in mass/length of spin axis or both) for the fixed value of ω_s, ω_p values increases.

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- The data tabulated and its analysis follows the theoretical formula, $\tau = mgr = I\omega_s\omega_p$

M = 100 kg			
W = 981N			
SL no	r (in m)	ωs (in rads-1)	ωp (in rads-1)
1	0.1	5	24.53
2	0.1	10	11.08
3	0.1	20	3.16
4	0.1	50	0.43
5	0.2	5	14.82
6	0.2	10	6.67
7	0.2	20	2.01
8	0.2	50	0.23
9	0.5	5	6.62
10	0.5	10	3.01
11	0.5	20	0.92
12	0.5	50	0.07

M = 200 kg			
W = 1962N			
SL no	r (in m)	ωs (in rads-1)	ωp (in rads-1)
1	0.1	5	41.30
2	0.1	10	16.09
3	0.1	20	5.86
4	0.1	50	4.18
5	0.2	5	22.85
6	0.2	10	16.40
7	0.2	20	6.95
8	0.2	50	2.66
9	0.5	5	9.01
10	0.5	10	3.78
11	0.5	20	1.62
12	0.5	50	1.22

Applications of Gyroscopic Action:

- Gyrocompass: If calibrated to point towards the true north, a gyroscope will serve as a practical compass due to the principle of rigidity in space. Unlike a magnetic compass that points towards the magnetic north as it gets affected by magnetic materials, a gyrocompass always points towards the true north.
- Artificial Horizon: A heavy flywheel with a large spin angular velocity is used in an altimeter. Owing to the principle of rigidity, even when the outer gimbals rotate as the aircraft pitches and rolls, the orientation of the spin axis of the flywheel will always be normal to the Earth's surface, and the true altitude can be calculated.
- Turn/Slip Indicator: As the aircraft rolls or pitches, the lightweight, low angular speed flywheel precesses accordingly. The device is calibrated to denote bank angles. This kind of turn indicator functions on the principle of precession. In another type of indicator, sensors are attached to the bearings of the revolute joints of the gimbals of the Gyroscope with a heavy, high-speed rotation flywheel. As the gimbals rotate to adjust for the change in angular momentum, the sensors pick up the change in values at the bearings and denote the corresponding angles as per calibration.
- Motorcycle Turning: One effect of turning the front wheel of a motorbike is the roll moment caused by gyroscopic precession. The roll will be opposite to the wheel turning direction. This is why racers always lean and tilt their bikes to a specific angle while taking turns. Else the gyroscopic effect would cause them to topple.

Possible Extensions:

- A self-balancing bicycle can be modelled such that the spin angular velocity of the bike changes to ensure the bicycle does not topple.
- Modelling and simulation of Steadicam (Camera in conjugation with several gyroscopes) used in the 1980s to shoot the famous Endor speeder bike chase in the movie Star Wars: Return of Jedi.

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