Applications of Gyroscopic Effect in Transportation

Tomáš Náhlík
Institute of Technology and Business in České Budějovice
Faculty of Technology
Department of Informatics and Natural Sciences
Czech Republic
e-mail: nahlik@mail.vstecb.cz

Dana Smetanová
Institute of Technology and Business in České Budějovice
Faculty of Technology
Department of Informatics and Natural Sciences
Czech Republic
e-mail: smetanova@mail.vstecb.cz

DOI 10.17818/NM/2018/4SI.24
UDK 53.082.16:656
Professional paper / *Stručni rad*
Paper accepted / *Rukopis primljen:* 28. 8. 2018.

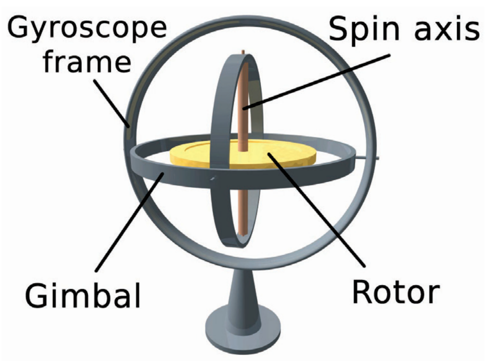
Summary

This article describes gyroscopes and their effects in various fields of everyday life. Gyroscopic effect is ability (tendency) of the rotating body to maintain a steady direction of its axis of rotation. The gyroscopes are rotating with respect to the axis of symmetry at high speed. Gyroscopic effect is related to all rotating mechanisms (wheels, gears, shafts, rotors, bicycles, motorcycles, children's toys...). In some cases, we want to enhance the gyroscopic effect (for stabilization, energy accumulation). Stabilization effect is mainly used for two-wheeled vehicles. It can be also used on ships and boats, where big wheel is rotating and preventing the boat to overturn. Gyroscopic effects can help with energy accumulation. The bigger rotating speed is achieved the bigger amount of energy is stored. When the gyroscope is well designed the efficiency can be much higher than in the batteries. In other cases we want to suppress or compensate it (in case of the direction change of the rotating device). This is mainly about the planes. When the pilot of the plane needs to change the heading then during the left turn the plane will go up and during the right turn it goes down. The use of gyroscopes is important in various modes of transportation. We describe different usage of gyroscopes in transport and logistics, especially gyrocompass (ships and planes – advantages: no influence by ferromagnetic materials, heading to the true North, disadvantages: errors caused by rapid changes in course, speed and latitude); attitude and heading indicators (plane); pendulous integrating gyroscopic accelerometer (rocketry); gyrostat - control moment gyroscope (space – stations, satellites and probes); MEMS gyroscope (automotive, entertainment, robots, etc.).

KEY WORDS
gyroscope
stabilization
transportation

1. INTRODUCTION

With gyroscopic effect we meet in everyday life. Each object which produces gyroscopic effect is a rotating gyroscope,. Knowledge about gyroscope movement is important for applications in different fields of physics (e.g. Larmor precession in atomism) and astronomy (lunisolar precession of Earth), in technology (e.g. gyroscopic effect in transportation [1-20].), in military (stabilization of missiles and bullets) and also in sport (flight disk), in energetics (kinetic energy accumulation by turbines, mechanical batteries).



Source: [21]

Figure 1 Model of gyroscope

Gyroscopic effect is ability (tendency) of the rotating body to maintain a steady direction of its axis of rotation. The gyroscopes are rotating with respect to the axis of symmetry at high speed. This gives them big kinetic energy

$$E = \frac{1}{2} I\omega^2, \quad (1)$$

where ω is angular speed and I moment of inertia of the form

$$I = \int_Q r^2 \mathrm{d}m, \quad (2)$$

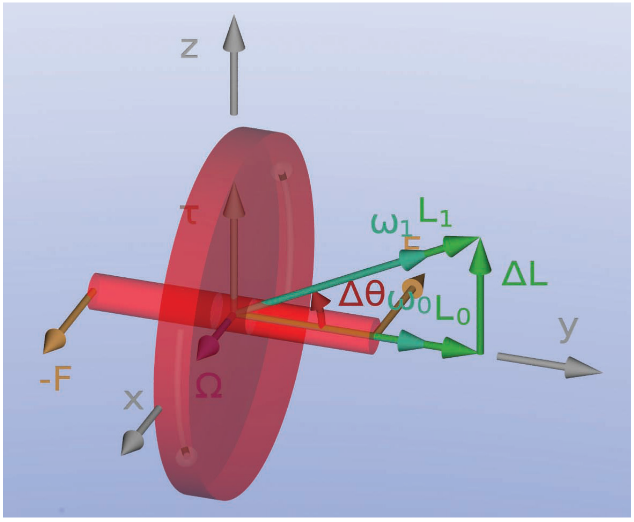
where Q is entire mass. The gyroscopic effect is dependent on the weight of the rotating body, the weight distribution around the rotation axis, and the angular speed.

The mathematical description of the problem is based on the equations of motion (second order partial differential equations). The equations of motion are well known as Euler-Lagrange equations. To resolve the problem it is necessary to use differential and integral calculus and theory of differential equations. The basis of exploring physical properties of the gyroscope is tied to the work of famous physicists and mathematicians.

The spatial rotation (appropriately described by angles) split into three parts was introduced by Leonard Euler in the middle of the 18th century and therefore the angles are called Euler angles. Lord Kelvin studied symmetrical gyrostats (see [18]) at the end of the 18th century. Sophie Kowalevski investigated the case where axis is not passing through the centre of gravity (see [22]) at the end of the 19th century.

2. APPLICATIONS OF GYROSCOPIC EFFECT

Gyroscopic effect is used not only in the logistic but also in the military. If the bullet is rotating around the longitudinal axis it is more stable and for example the side wind doesn't have so big effect on it.



Source: [23]

Figure 2 Physical description of the gyroscope

Sometimes the gyroscopic effect complicates things. When the pilot of the plane needs to change the heading then during the left turn the plane will go up and during the right turn it goes down. This is caused by the vector properties of the gyroscope (see figure 2).

$$\boldsymbol{M} = \boldsymbol{\omega} \times \boldsymbol{L} \quad (3)$$

Where M is moment, ω is angular speed and L angular momentum.

The use of gyroscopes in logistics can be divided into several groups:

- Stabilizers
- Energy storage
- Gyrocompass
- Attitude and Heading indicator
- Pendulous Integrating Gyroscopic Accelerometer (PIGA)
- Gyrostat - Control moment gyroscope (CMG)
- MEMS Gyroscope

2.1. Stabilizers

Rotating objects like wheels are used as stabilizers for two-wheeled vehicles – bicycles and motorbikes.

This stabilization effect is used also on ships. Gyroscopes are used as anti-roll stabilizers. In the past, in the 19th and early 20th centuries they were used also on big ships. Nowadays they are mounted on the small personal ships, yachts and motorboats. The bigger the boat is the bigger gyro is needed, bigger gyro produces bigger anti-rolling torque.

2.2. Energy storage

The main principle of flywheel energy storage (FES) is to store energy of the system as a rotational energy. The process of extracting energy from the system decreases the flywheels' rotational speed. Storing energy in the FES results in the higher rotational speed.

The amount of specific energy (eq. 4) stored in the system depends on several factors, the first is the geometry of the rotor and the second are the properties of the material used for flywheel.

$$\frac{E}{I} = K\left(\frac{\sigma}{\rho}\right) \quad (4)$$

Where E is kinetic energy of the rotor in Joules (eq. 1), I is rotor's moment of inertia (eq. 2), K rotor's geometric shape factor ($[K] = m^{-2}$), σ is tensile strength of the material ($[\sigma] = Pa$) and ρ is density of the material ($[\rho] = kg \cdot m^{-3}$). This is valid only for single-material and isotropic rotors.

Storage efficiency depends on the orientation and design of the flywheel. In the worst case, with the mechanical bearing and wrong orientation, it can lose up to 50% of energy in two hours. [24]. Mechanical efficiency can be increased using magnetic bearing and high vacuum up to 97% [25].

The principle of energy storage is used also in the automotive industry in various hybrid or electrical cars instead of batteries or as a system for the recuperation of energy.

Flywheels are used in the physics laboratories where high currents for brief intervals are needed.

Several flywheel grid energy storages are installed on different places on Earth [25].

2.3. Gyrocompass

Gyrocompass is widely used in sea transport. It has two main advantages over the classical magnetic compass. Instead of classical compass the gyrocompass seeks for the true north determined by the Earth rotation. And gyrocompass is not influenced by ferromagnetic materials, such as in a ship's steel hull, which distort the magnetic field [6].

Gyrocompass suffers from certain errors. These errors are introduced during rapid changes in course, speed and latitude. These deviations are caused before the gyroscope can adjust itself and are called steaming error [9].

2.4. Attitude and Heading Indicators

The Attitude Indicator, known as the artificial horizon, is used in aviation. This device informs the pilot about the orientation of the aircraft relative to the Earth's horizon. It indicates pitch – tilt in the horizontal plane around the axis perpendicular to the direction of movement of the aircraft (fore and aft tilt) – and bank – tilt in horizontal plane around the axis which has the same direction as the movement of the aircraft (side to side tilt).

Attitude indicators called Flight Director Attitude Indicators (FDAIs) are used on manned spacecraft. They indicate the craft's yaw angle (nose left or right), pitch (nose up or down), roll, and orbit relative to a fixed-space inertial reference frame, for which FDAI can be configured to use the known positions relative to Earth or the stars.

The Heading Indicator informs pilot about the heading of the aircraft. It is used in the same meaning as magnetic compass which suffers from several types of errors. However the heading indicator is not perfect. Heading indicator drifts over time. This drift of the gyroscope can be easily predicted based on its physical properties, time of operation and also the position or changes of position in space. Due to this, the drift heading indicator has to be calibrated each 10 to 15 minutes [1].

2.5. Pendulous Integrating Gyroscopic Accelerometer

A PIGA is a gyroscopic type of accelerometer which can measure acceleration and speed simultaneously. Speed is measured by integration of acceleration against time. PIGA is used in Inertial Navigation Systems (INS) for guidance of aircrafts and missiles (not only ballistic missiles but also Titan and Saturn – used in US space program). Advantages of PIGA are very high sensitivity and accuracy over wide acceleration range.

2.6. Gyrostat

A Gyrostat consists of a massive gyroscope and solid casing (see [18], [26]). In the 19th and early 20th centuries the gyrostats were used for stabilizing the ship (Anti-rolling gyroscope).Today gyrostats are used for stabilization of the slowly moving ships (hydrodynamic roll stabilizer fins are ineffective) and for attitude control systems for spacecraft and satellites, where they are known as gyrodynes or control moment gyroscopes (CMGs).

CMGs are used from the beginning of space flight because all spacecraft need to know their orientation in space and mainly to keep the same orientation at low cost of propellants (i.e. in the first two years gyrodynes on MIR save about 15 tons of propellants [16]).

ISS CMG Specification (see [4] and [8]):

- 4 gyroscopes
- Angular momentum: 4760 Nms
- Nominal speed: 6600rpm (691 rad/s)
- Maximum Output Torque: 258Nm
- Weight: 272 kg each
- Place: Z1 truss of ISS

MIR CMG (gyrodynes) specification [16]:

- 12 gyrodynes
- Weight: 165kg each
- Nominal speed: 10000rpm (1047 rad/s)
- Place: 6 – module Kvant-1, 6 – module Kvant-2

2.7. MEMS Gyroscope

MEMS – a microelectromechanical systems gyroscope is a miniaturized gyroscope found in different electronic devices. It takes the idea of the Foucault pendulum and uses a vibrating element. MEMS gyroscopes are used in the automotive industry where they serve as an input for to electronic stability control systems in conjunction with a steering wheel sensor or airbag systems.

MEMS gyroscope can be found also in industrial robots, where it helps with the high precision positioning and movement, in spacecraft (see [2], [14], [17]). Due to their small size MEMS gyroscopes can be used in the field of entertainment (smartphones, gaming devices), hobbies (RC flying models, camera and video systems – image stabilization).

3. CONCLUSION

There are a lot of interesting and various problems in the field of transport and logistics. One of the problems is related to rotating mechanisms. Many rotating mechanisms (wheels, gears, shafts, rotors...) are used during the transport process. The rotating parts with gyroscopic effect of the transportation are studied in [7], [10], [11], [13], [19], [20]. We have to model their properties as a gyroscope. In some cases, we want to enhance the gyroscopic effect (stabilization) and in other suppress or compensate for it (change of direction of rotating device).

In [10], a mathematical model of combined bending-gyratory vibration is presented. Especially the paper is devoted to the application of the finite element method. The mathematical model based on the physical discretization and used for solving the problem of finding critical speed of rotations is made in [11]. The finite element analysis for a functionally graded rotating shaft with multiple breathing cracks is presented in [7]. The set of steady-state conditions for the movement of the tractor-lorry-trailer combination model is determined on the basis of the developed mathematical model; it provides the necessary mobility for the passage of the circular overall traffic lane [27].

The design of an active stabilizing system (ASAS) for a single-track vehicle is presented in the study [3]. Using the gyroscopic effects of two gyroscopes, this system can generate control torque to stabilize the vehicle in cases where there is centrifugal force of turning. The stabilization of systems is also studied in articles [5], [12], [15]. The stabilization effect of the gyroscope is also used in the popular personal vehicle called Segway.

The use of gyroscopes is important in various modes of transportation. This paper describes different usage of gyroscopes in transport and logistics, especially gyrocompass (ships and planes); attitude and heading indicators (plane); pendulous integrating gyroscopic accelerometer (rocketry); gyrostat - control moment gyroscope (space – stations, satellites and probes); MEMS gyroscope (automotive, entertainment, robots, etc.).

REFERENCES

[1] Bowditch, N. American Practical Navigator, Paradise Cay Publications, 2002, pp.93-94. ISBN 978-0-939837-54-0.

[2] Cassini-Huygens probe - Jet Propulsion Laboratory, "Cassini Spacecraft and Huygens Probe," p. 2, online. Available on: https://saturn.jpl.nasa.gov/legacy/files/space_probe_fact.pdf.

[3] Chu, T. D., Chen, C. K. Design and Implementation of Model Predictive Control for a Gyroscopic Inverted Pendulum. Applied Sciences, 2017, Vol. 7, No. 12, 1272. https://doi.org/10.3390/app7121272

[4] CMG – Control Moment Gyro, online. Available on: http://www2.l3t.com/spacenav/pdf/datasheets/CMG.pdf.

[5] Deng, J. Stochastic Stability of Gyroscopic Systems Under Bounded Noise Excitation. International Journal of Structural Stability and Dynamics, 2018, Vol. 18, No. 02, 1850022. https://doi.org/10.1142/S0219455418500220

[6] Elliott-Laboratories. The Anschutz Gyro-Compass and Gyroscope Engineering, 2003, pp. 7-24. ISBN 978-1-929148-12-7. Archived from the original on 2017-03-04.

[7] Gayen, D. et al. Finite element analysis for a functionally graded rotating shaft with multiple breathing cracks. International Journal of Mechanical Sciences, 2017, Vol. 134, pp. 411-423. https://doi.org/10.1016/j.ijmecsci.2017.10.027

[8] Gurrisi C. et al. Space Station Control Moment Gyroscope Lessons Learned, NASA, [online]. Available on: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100021932.pdf.

[9] Gyrocompass: Steaming Error Archived 2008-12-22 at the Wayback Machine., Navis. Accessed 15th December 2008.

[10] Hrubý, P. et al. Proposal Mathematical Model for Calculation of Modal and Spectral Properties. In: Bastinec, J., Hruby, M. Conference on Mathematics, Information Technologies and Applied Sciences Location: Univ Defence Brno, Brno, Czech Republic Date: JUN 15-16, 2017, pp. 131-140.

[11] Hrubý, P. et al. Mathematical Modelling of Shafts in Drives, In: Lucas Jódar, Juan Carlos Cortés and Luis Acedo, Modelling for Engineering & Human Behaviour 2017, Instituto Universitario de Matemática Multidisciplinar, Universitat Politécnica de Valéncia, 2017, pp. 223-228. ISBN 978-84-697-8505-8.

[12] Jalili, M. M., Emami, H. Analytical solution for nonlinear oscillation of workpiece in turning process. In: Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2017, Vol. 231, No. 19, pp. 3479-3492. https://doi.org/10.1177/0954406216650471

[13] Peng, C. et al. A Novel Cross-Feedback Notch Filter for Synchronous Vibration Suppression of an MSFW With Significant Gyroscopic Effects. IEEE Transactions on Industrial Electronics, 2017, Vol. 64, No. 9, pp. 7181-7190. https://doi.org/10.1109/TIE.2017.2694402

[14] Pivarčiová, E. et al. Analysis of control and correction options of mobile robot trajectory by an inertial navigation system. International Journal of Advanced Robotic Systems, 2018, Vol. 15, No 1. https://doi.org/10.1177/1729881418755165

[15] Polekhin, I. On impulsive isoenergetic control in systems with gyroscopic forces. International Journal of Non-Linear Mechanics, 2018. https://doi.org/10.1016/j.ijnonlinmec.2018.01.001

[16] Portree D. S. F. Mir Hardware Heritage. NASA, 1995.

[17] Qazizada, M.E., Pivarčiová, E. Mobile robot controlling possibilities of inertial navigation system. Procedia Engineering, 2016, Vol. 149, pp. 404-413. https://doi.org/10.1016/j.proeng.2016.06.685

[18] Thomson, W. Vibrations and Waves in a stretched uniform Chain of Symmetrical Gyrostats. Proceedings of the London Mathematical Society, 1874, Vol. 1, No. 1, pp. 190-200. DOI: 10.1112/plms/s1-6.1.190. https://doi.org/10.1112/plms/s1-6.1.190

[19] Wang, M. et al. Modal characteristics and unbalance responses of fan rotor system with flexible support structures in aero-engine. In: Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2017, Vol. 231, No. 9, pp. 1686-1705. https://doi.org/10.1177/0954410016658076

[20] Zheng, S. et al. Tracking Compensation Control for Nutation Mode of High-Speed Rotors with Strong Gyroscopic Effects. IEEE Transactions on Industrial Electronics, 2018, Vol. 65, No. 5, pp. 4156-4165. https://doi.org/10.1109/TIE.2017.2767559

[21] Online. Available on: https://commons.wikimedia.org/w/index.php?curid=1244193.

[22] Kowalevski, S. Sur le probleme de la rotation d'un corps solide autour d'un point fixe. Acta Mathematica, Vol. 12, No. 1, 1889, pp. 177-232. https://doi.org/10.1007/BF02592182

[23] Online. Available on: https://commons.wikimedia.org/wiki/File:Gyroskop_und_Praezession.png.

[24] Rosseta Technik GmbH, Flywheel Energy Storage, German, retrieved February 4, 2010. Available on: http://www.rosseta.de/srsy.htm

[25] Wayback Machine. Available on: https://en.wikipedia.org/wiki/Wayback_Machine

[26] Gray, A. A Treatise on Gyrostatics and Rotational Motion: Theory and Applications (Dover, New York)), 1979.

[27] Sakno, O., Moysya, D.L. Kolesnikova, T. Dynamic stability of a model of a tractor-lorry-trailer combination. Scientific Journal of Silesian University of Technology. Series Transport. 2018, 99, 163-175. ISSN: 0209-3324. https://doi.org/10.20858/sjsutst.2018.99.15