

Damping A Passenger Car With A Gyroscopic Damper System

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ABSTRACT

Today, body vibration energy of passenger cars gets dissipated by linear working shock absorbers. A new approach substitutes the damper of a passenger car by a cardanic gimbaled flywheel mass. The constructive design leads to a rotary damper in which the vertical movement of the wheel carrier leads to revolution of the rotational axis of the flywheel. In this arrangement, the occurring precession moments are used to control damping moments and to store vibrational energy. Different damper characteristics are achieved by different induced precession. From almost zero torque output to high torque output, this damper has a huge spread.

Next to the basic principal, in this paper an integration in the chassis, including a constructive proposal is shown. A conflict with high torque and high angular velocity leads to a special design. Moreover concepts to deal with all vehicle situations like yawing, rolling and pitching are shown. Since the gyroscope acts in global world coordinate system the movement of the vehicle has to be considered. This leads to a special control of all for systems together regarding different direction of the flywheels angular velocity.

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INTRODUCTION

The standard approach for dissipating the vibrational energy of passenger car bodies is the use of telescopic hydraulic shock absorbers. A first aspect of such a damping concept is the linear acting principal. This damper claims a certain construction height and limits the required space of e.g. luggage space or tire scope. A second aspect is the fact that the hydraulic principal dissipates kinetic energy into heat.

In the state of the art there is no damper which works in rotational principal in a mass-production vehicle. Even if there is no mass-production damper with the capability to gain kinetic energy there are a lot research projects on this topic.

Scientifically proven is the fact that there is a possibility to gain energy from dampers. Papers like [1] and [2] identify an energy potential of up to 400 Watt per vehicle. But the exact amount of energy recuperation depends on the unevenness of the road. On a highway there is less potential to recuperate energy than on a bad country road. Different damping concepts try to gain this kinetic energy potential with a generator. Damping systems used in [3] and [4] use a mechanical gearbox to transform the vertical movement of the wheel carrier in a state of motion which is useful for an electrical generator. A fast rotation of the generator with a low torque is considered as useful because of manufactured size and weight.

Besides there are solutions like [5] which use a hydraulic transmission to drive an electric generator. Other solutions without a transmission like [6] damp the movement directly with magnetic fields.

All mentioned concepts have disadvantages. A gear box transmits the inertia of the generator to a higher level and leads to a stiffer connection of the damper at high frequencies. The transformation from hydraulic to mechanical motion entails a loss of energy. The avoidance of a gear box has to be paid with manufactured size and weight.

Next to applications from automotive engineering there are gyroscopic systems like [7] and [8] which gain energy from wave movement. In those systems a floating body follows the wave movement. The outer part of a two-axis cardanic gimbaled gyroscope follows the housing of the floating body. In the inner part the gyroscope rotates with high revolutions. The outer movement leads to a gyroscopic induced slewing. This is connected and damped with an electric generator.

Another example is [9]. In this paper oscillations of a ropeway get damped by a gyroscopic arrangement. A passive damping of the precession induced movement is shown. Moreover a widespread use of the gyroscopic effect is the roll stabilization of vessels like covered in [10].

A lot of systems with no or small contact to earth use the gyroscopic effect to support their own orientation. Additionally to stabilization the precession induced relative velocity can be used for energy storage.

Altogether the gyroscopic systems deal with alternating motions and have little input torque of a generator with a huge output torque on the outer shaft.

The requirements on a rotational damper are quite similar. The wheel carrier has alternating oscillations and the damping of these oscillations requires a high torque. Since a control motor to control the precession movement is needed, the kinetic energy can be stored as electric energy instead of dissipate it to heat. According to [11] it is a proper approach to use a gyroscopic damper system as a shock absorber in passenger cars.

How does the design of such a gyroscopic damper system looks like and what are the problems in the daily use of a passenger car? In order to investigate these questions this paper will serve as a proposal.

First a constructive design is given and special challenges are pointed out. For instance a bearing has to deal with a huge torque and high angular velocity at the same time. Second gyroscopic laws occur not only in the cars coordinate system but also in global world coordinate system. This means a moving car interacts with the gyroscopic damper and the other way around.

METHODS AND MATERIALS

A flywheel mass is mounted in a cardanic gimbal. Figure 1 shows the arrangement including the coordinate system. There are three pivots. In the inner axis the flywheel mass rotates around angle φ . Perpendicular to the rotational axis of the flywheel an inner ring is pivoted with angle θ . Not in the same plane but perpendicular to both angles φ and θ an outer ring is gimballed with angle ψ . The coordinate system is proposed in [12].

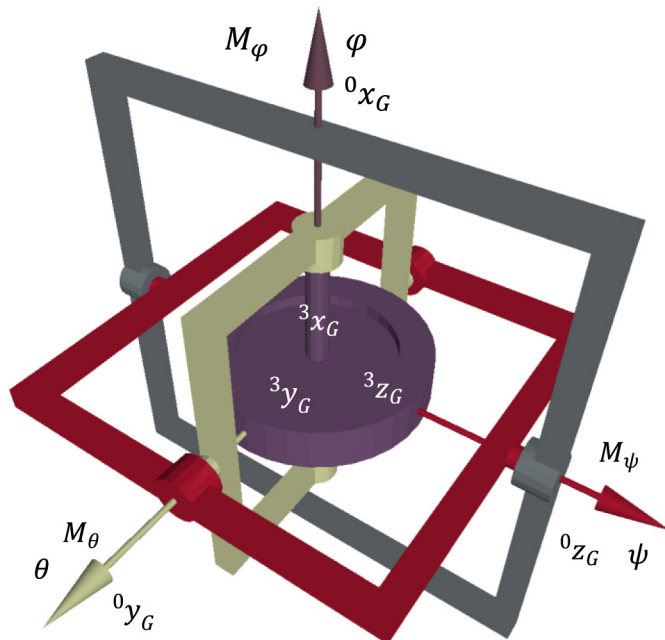


Figure 1. Principal arrangement of the gyroscopic damper system.

According to [12] a moving gyroscope has three angular velocities. There is nutation, precession and spin. All three angular velocities are perpendicular to each other and create the mentioned torques M_θ and M_ψ . Assmann shows in [13] that in the body orientated coordinate system the motion of the body influences the torque $\vec{M}$ with

$$\vec{M} = \frac{d}{dt}(J \cdot \vec{\omega}). \quad (1)$$

In equation (1) the inner flywheel mass has the angular velocity ${}^3\vec{\omega}$ and the inertia tensor J with

$$J = \begin{bmatrix} J_\varphi & 0 & 0 \\ 0 & J_\theta & 0 \\ 0 & 0 & J_\psi \end{bmatrix}. \quad (2)$$

In order to achieve a damper system the use of the torques M_θ and M_ψ around angles φ and θ are essential. An input of motion at angle ψ leads to disturbance of axis of the angular velocity of the flywheel. This induces a movement at angle θ resulting from precession. If there is torque M_θ which is orientated against the direction of $\dot{\theta}$, there is a resulting torque M_ψ . Since the torque M_ψ and the angular velocity $\dot{\theta}$ are proportional, there is the possibility to use this concept as a cars shock absorber. This is shown in [11].

The equation of motion for the torque M_ψ with

$$M_\psi = (2J_\varphi - 2J_\psi)\dot{\theta}\dot{\psi} s\theta c\theta - J_\varphi\dot{\phi}\dot{\theta} c\theta + (J_\psi - J_\varphi)\ddot{\psi} c\theta^2 - J_\varphi s\theta \ddot{\phi} + J_\varphi\ddot{\psi} \quad (3)$$

is derived from equation (1) with respect to the coordinate system introduced in [12] and applied in [11]. A simplification of $J_\theta = J_\varphi$ is assumed.

DAMPER DESIGN

In order to use the gyroscopic damper in a real car a constructive design is necessary. In figure 2 the total view of the gyroscopic damper system is shown. The whole damper is mounted with the outer grey elements. With these elements the damper is connected to the body of a passenger car. At the bottom of figure 2 a joint or hinge is shown. With this hinge the damper is connected to the wheel carrier of the passenger car. The connection of a moving wheel carrier to the gyroscopic damper has to fulfill the restriction in movement. This means a connection must transmit only push and pull forces to the gyroscopic damper. In this arrangement the force F_ψ can be regarded as damper force.

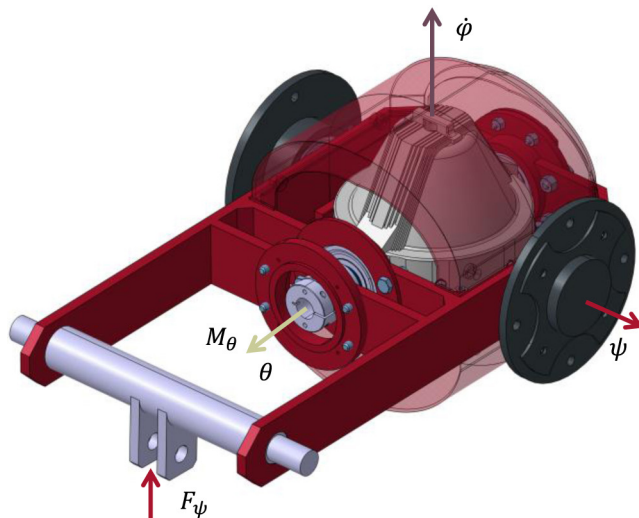


Figure 2. Design of the gyroscopic damper system (total view).

The torque M_θ controls the movement from precession around angle θ with an electric motor. This electric motor is not shown due to clarity. Covered by a transparent enclosure the inner ring is shown in beige. The dimension of the outer red ring is chosen that the inner ring pivots around angle θ with $-\pi/2 < \theta < \pi/2$. An angle with a higher magnitude for θ is not recommended since there is a singularity of the system for $\theta = k \cdot \pi/2$ with $k \in \mathbb{Z}$. A closer look on [equation \(3\)](#) and [\[11\]](#) makes this obvious.

The whole construction is made of aluminum due to weight reduction. There is one part where weight reduction is not recommended. This is the turning flywheel mass itself. There is a conflict between weight reduction and big inertia tensor J . Following the flywheel mass is made of steel and has an outer diameter of 15 cm.

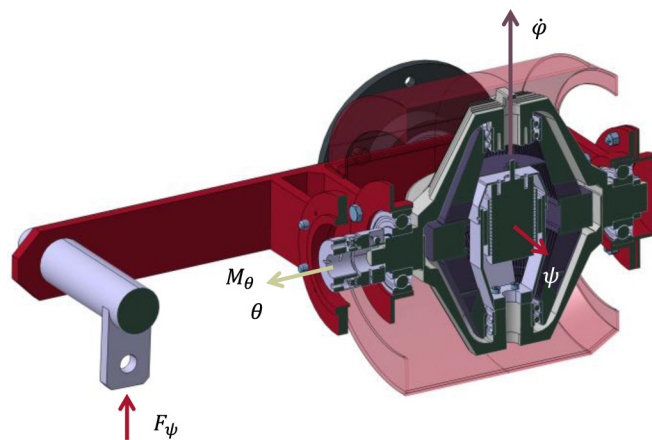


Figure 3. Design of the gyroscopic damper system (section view).

The sectional view of the gyroscopic damper system is shown in [figure 3](#). The cutaway plane is identical with x-y-plane from [figure 1](#). Included in the beige inner ring which pivots around angle θ there is the flywheel mass (in color purple). Two roller bearings on two sides are used to realize angle ϕ . The outer shaft of the roller bearing is connected to the gyroscopic flywheel mass. This flywheel mass

consists of a circular ring with a squared cross section. As mentioned this ring is made of steel. Two cones are used to connect the flywheel mass to the roller bearings.

The angular velocity $\dot{\phi}$ is achieved by a little electric motor. This motor is mounted directly on the inner ring (angle θ) and placed in the available volume of the gyroscopic flywheel mass.

The roller bearings for the gyroscopic flywheel mass have an angular contact. In order to achieve a bigger support for the transmitted torque a O-arrangement was chosen. The other bearings are designed as thrust bearing and floating bearing. There is no need of a special lubrication concept since the bearings are sealed and have their own grease.

The design has to fulfill several requirements. First there is a high angular velocity necessary for the gyroscopic flywheel mass. The higher the angular velocity the bigger the damping torque M_ψ or the equivalent damper force F_ψ . The phenomenon of the gyroscopic effect generates all torques of the turning flywheel mass. The spin initializes the effect. As precession occurs a moving angle ψ leads to a moving angle θ . The only connection of the flywheel mass to the inner ring (beige) is realized with the two times two roller bearings. A high torque with high angular velocity is an adverse combination. Bearings with small diameter are capable to realize high angular velocities. Bearings with a big diameter are capable to support high forces. In this concept an outer diameter of the bearings of 55 mm was reasonable.

Second the electric motor which generates the angular velocity $\dot{\phi}$ needs cooling. But a huge flow rate of air could lead to disturbing noise. The relative velocity between the electric motor and the gyroscopic fly wheel mass is very high since the angular velocity $\dot{\phi}$ will be about 2500 rad/s. In this concept a conduction of heat is achieved. The use of aluminum is reasonable since the material has a thermal conductivity of 235 W/m/K. Cooling fins on the outside of the beige inner ring support the effect.

Third there are arrangements to achieve a quiet running smoothness of the gyroscopic flywheel mass. The fan effect is reduce with inner ribs at the flywheel mass. Moreover the distance of the ribs is asymmetric. A single whistle at one frequency gets prevented and a bigger frequency range at a lower sound power will occur.

For a given vehicle size and reasonable rotational speed a size for the turning mass was found with

$$J = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 0.5 \end{bmatrix} \cdot 0.01 \text{ [kg m}^2\text{]} \quad (4)$$

A realization of J in real construction leads to the data in [table 1](#).

Table 1. Data for the constructive realization of the rotating element.

Mass	3 kg
Outer diameter of rotating inertia	15 cm
Material	Steel