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An Axiomatic Design approach for a motorcycle steering damper

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Abstract

The main function of a motorcycle steering damper is to stop the steering oscillations that could be generated during the vehicle motion around the steering axis, a typical motorcycle instability known as wobble or shimmy. However, in normal conditions, the damping function of the device on the steering can be harmful, causing rider's wearying and thus decreasing his comfort and safety. Moreover, a recent trend of steering dampers is the size optimization with a higher integration of the device into the steering head and consequent greater constraints on its dimensions. In this paper, a model of motorcycle is considered to define the damping factors generally required on the steering axis to ensure safety and comfort in all conditions. Moreover, an Axiomatic Design approach is used to analyze the critical aspects and to propose an innovative architecture for a steering damper based on magneto-rheological (MR) fluid and fully integrated in the steering head of the motorcycles.

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Keywords: Axiomatic Design, Steering Damper, Magneto-rheological Fluid

1. Introduction

Active safety is a more and more important topic in the field of road vehicles. The prevention of accidents and dangerous situations has become as necessary as the passive safety, in order to preserve road users security in every condition.

Regarding motorcycles, due to the increasing performance of both scooters and motorbikes, the active safety has become a crucial issue [1-4].

There are many critical points regarding the instability in motorcycles that have been studied in literature. One of the most dangerous, known as *wobble* or *shimmy*, consists in a steering oscillation around the steering axis [5,6]. Such instability, subsequently described in detail, is extremely dangerous and is perceived as a sudden reaction of the steering. If, in some cases, this phenomenon constitutes a simple noise to the ride, it is also true that, at high speeds, it is generated and amplified in a very short time, acting on frequencies too high to be controlled by the rider. In order to solve this instability, some commercial steering dampers are installed on many motorcycles. The main function of a motorcycle steering damper is in fact to stop the steering oscillations of the wobble with an adequate damping torque on the steering axis, causing however rider's wearying in normal riding conditions because of the higher hardness of the steering.

Since, in recent years, the market trend is to offer faster and faster scooters, closer to the motorbikes performance, the need of a steering damper has risen even for some models of scooters. On the other hand, motorbikes users require powerful vehicles that are however able also to offer an easy and comfortable riding in the traffic and during non-extreme rides.

Even if the performance of scooters and motorbikes is getting closer and closer, the scooters still generally prefer a steering softer than the motorbikes since their use is expected mainly in the city traffic at low speeds, while motorbikes often have a harder steering as their prevalent use is out of the city at higher speeds. Anyway, the classical distinction between scooters and motorbikes is becoming less and less clear than in the past.

Moreover, in order to improve the system efficiency, a recent trend in steering dampers is the size optimization with a higher integration of the device into the steering head and consequent greater constraints on its dimensions [7].

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In this paper, we consider a model of motorcycle [8] to define the damping coefficients generally required on the steering axis to ensure safety and comfort in all conditions.

Furthermore, an Axiomatic Design approach is used to analyze the critical aspects and find a new concept of a steering damper, based on magneto-rheological (MR) fluid and fully integrated in the steering tube.

Nomenclature

MR	Magneto-rheological
FRs	Functional Requirements
DPs	Design Parameters
DM	Design Matrix
CSTRs	Axiomatic Design Constraints
c	Steering damper damping coefficient
c_{max}	Maximum steering damper damping coefficient
c_{med}	Avarage steering damper damping coefficient
c_{min}	Minimum steering damper damping coefficient
V	Vehicle speed
K_λ	Motorcycle limber stiffness
f	Wobble frequency
a_n	Motorcycle trail
I_A	Limber inertia around steering axis
δ	Steering axis
ε	Motorcycle steering tilt
ω	Wobble pulsatance
ξ	Steering damping ratio
D_E	Stator outer diameter
h	MR Steering damper height (or stator height)
H	Magnetic field intensity

2. The steering damper in motorcycles

2.1. The wobble instability in motorcycles

A motorcycle has several degrees of freedom, that correspond to the elementary movements the vehicle can make. In particular, the so called *in-plane movements* are the degrees of freedom of the vehicle within its median plane, while the *out-of-plane movements* are the degrees of freedom out of its median plane [9]. Generally, the onset of eigenmodes in a motorcycle is due to the simultaneous variation of several degrees of freedom.

In particular, the wobble mode is a motorcycle instability which consists of a steering oscillation around its rotation axis. The wobble frequencies usually vary between 4 and 10 Hz [8]. The phenomenon begins with small steering oscillations of few degrees that, if not promptly damped, in the most severe cases can turn into a violent movement of the handlebar from one extreme to the other, commonly called *tank slapper*. The wobble mode can be assumed independent from rear and roll movements. In this way, the motorcycle model developed by Cossalter [9] can be simplified in a model with only one degree of freedom, i.e. the rotation around the steering axis. The said model is represented in Fig. 1, where δ is the steering axis, ε the steering tilt, a_n the motorcycle trail, V the vehicle speed and θ the steering angle.

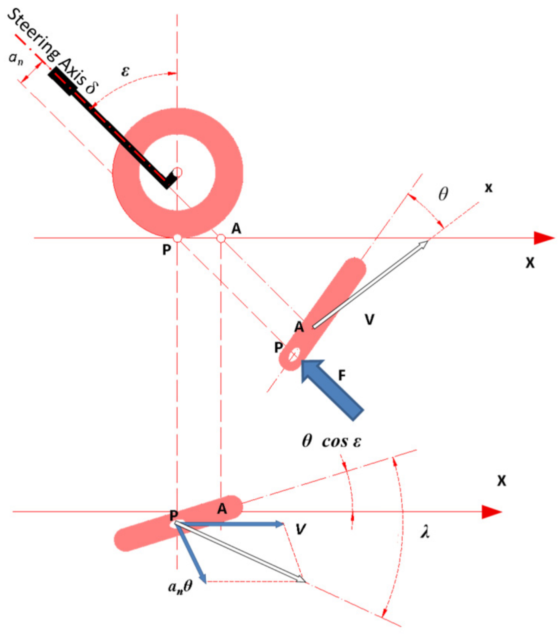

Fig. 1. Motorcycle model with one degree of freedom.

The wobble pulsatance ω and the damping ratio ξ of the system shown in Fig. 1 are described in equations (1) and (2) and are both influenced by the limber inertia relative to the steering axis (I_A), the trail (a_n), the stiffness of the tire and the fork (K_λ), the vehicle speed (V), the steering tilt (ε) and the damping coefficient of the steering damper (c):

$$\omega = \sqrt{\left(\frac{cV + K_\lambda f a_n^2}{2 I_A V}\right)^2 - \frac{K_\lambda a_n \cos\varepsilon}{I_A}} \qquad (1)$$

$$\zeta = \frac{cV + K_\lambda a_n^2}{2V\sqrt{I_A K_\lambda a_n \cos\varepsilon}} \qquad (2)$$

From equations (1) and (2) it can be seen that the wobble is strongly influenced by the motorcycle geometry. In addition, from equation (2) it can be noted that the damping ratio, without the steering damper, tends to zero with the increase of the vehicle speed.

2.2. The function of the steering damper

As shown in section 2.1, the use of the steering damper in motorcycles is increasing more and more in order to fight the wobble at high speeds. In this context, Sharp and Limebeer [8] created a motorcycle model to study the wobble mode stability. The results, obtained through formulas similar to the equations (1) and (2), are shown in Fig. 2, which represents the root loci for a motorcycle in straight running referred to the wobble mode.

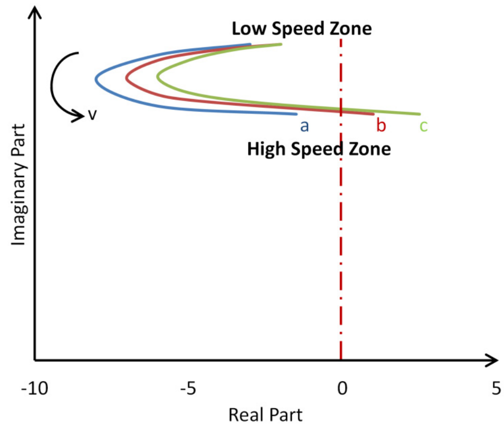

Fig. 2. Root loci for a motorcycle in straight running referred to the wobble. Speed v from 0.1m/s to 70 m/s. The steering damping changes from 7 Nms/rad (a) to 4 Nms/rad (b) and 0.9 Nms/rad (c).

At the starting value of the steering damping, equal to 7 Nms/rad, the wobble is damped across the whole speed range. However, the dependence on the parameter change is so high that, by reducing the value of the steering damping, the behavior of the vehicle quickly degenerates. At the value of 0.9 Nms/rad the wobble is not damped at high speeds, resulting in an extremely unstable condition.

The damping coefficient of the steering damper is therefore basic for the stability of motorcycles, especially at high speeds. However, the damping action has also some disadvantages, such as an excessive hardness of the steering during stationary maneuvers or in the traffic, an increased rider wearying in winding roads and a reduced feeling of the rider with the front wheel (both because of the greater hardness of the steering). All these aspects can be summed in a lower riding comfort in normal riding conditions (i.e. without wobble).

3. Axiomatic Design approach for steering dampers

In this study, an Axiomatic Design approach has been used to identify a new conceptual solution of a steering damper. From an Axiomatic Design point of view, motorcycle steering dampers are characterized by two functional requirements (FRs):

FR_1 – Safety: setting the wobble dampening.
FR_2 – Comfort: maintaining a comfortable riding.

It is very important to note that, since it is not possible to predict the onset of the wobble, both FRs are always requested simultaneously by the motorcycles users.

Both FRs are strongly dependent on the steering damping. As seen in the equation (2), the damping ratio ξ can be divided into two components, one dependent on the geometric and physical properties of the motorcycle, one dependent on the damping coefficient *c* provided by the steering damper.

Since the factors that determine the geometric component of the damping ratio are characteristic of each motorcycle and often can't be changed without upsetting the whole vehicle configuration, this article will focus on the component dependent only on the steering damper.

From now on, referring to the steering damping, it will be thus considered only the damping coefficient *c* of the steering damper instead of the total damping coefficient.

As shown in section 2.1, the damping coefficient *c* of the steering damper is fundamental to stop the steering oscillations at high speeds. So it can be used, for example, the damping coefficient of the steering damper as a DP to achieve the FR_1. Unfortunately this DP, that is constant for conventional steering dampers, affects even the rider comfort, as shown in equation (3):

$$\begin{Bmatrix} FR_1\text{: Dampening wobble} \\ FR_2\text{: Mantaining comfort} \end{Bmatrix} = \begin{bmatrix} X \\ X \end{bmatrix} \{DP\text{: Damping coefficient}\} \quad (3)$$

This leads to coupling, as the number of FRs exceeds the number of DPs and it is not possible to satisfy the two FRs independently [10,11]. As shown in Fig. 3, in practice the damping coefficient *c* is chosen high for the motorbikes in order to dampen the wobble at high speeds, while it is chosen low or zero (i.e. no steering damper) for city scooters in order to get a comfortable riding in the city traffic and at low speed, as already mentioned in section 1.

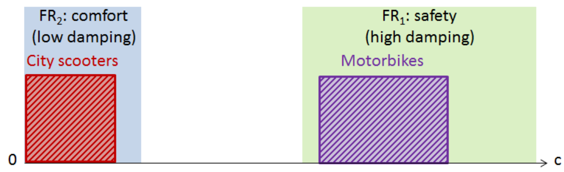

Fig. 3. Typical damping values chosen for city scooters and motorbikes.

As a consequence, scooters users get a comfortable ride in every condition but their safety is not ensured at high speeds since their steering damping is too low to stop the wobble, while motorbikes users get their safety ensured over the whole speed range but can't get a comfortable ride since their steering damping is high. For both scooters and motorbikes the solution is not ideal, since it is possible to satisfy only one FR at a time.

Referring to the considerations of section 1, which underlines that the performance and the needs of motorcycles and scooters in general are increasingly approaching, from now on, for this work, the application of the steering dampers will be only referred to an ideal vehicle, called "comfortable motorbike", that collects the characteristics and needs of both kind of motorcycles, i.e. high performance and speed together with a high comfort in traffic and during non-extreme rides. For this type of vehicle it can be observed that the traditional steering dampers are not able to satisfy simultaneously the two FRs, but at most only one at a time, as already shown in the equation (3).

Moreover, analyzing in detail the considerations made up to now on the wobble and the driving conditions of the vehicle, it can be observed that the high damping torque is required only for a few moments (fractions of a second, just during the onset of the wobble), while most of the time the damping torque must be very low (ideally zero). It can be concluded that the ideal steering damper should provide a very low average torque to guarantee the comfort, but also should be able to provide at any time peaks of torque high enough to dampen the wobble in the bud.

The idea is thus to install a steering damper with a variable action, i.e. able to modify at any time its damping coefficient from a low value (almost zero) in normal conditions, to a high value in dangerous conditions. This paper proposes a novel conceptual design for a motorcycle steering damper with a variable damping coefficient, found through an Axiomatic Desing approach and described in detail in chapter 4.

With this kind of steering damper the Design Matrix (DM) is then decoupled, as shown in equation (4):

$$\begin{Bmatrix} FR_1\text{: Dampen wobble} \\ FR_2\text{: Mantain comfort} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_1\text{: } c_{max} \\ DP_2\text{: } c_{med} \end{Bmatrix} \quad (4)$$

where c_{max} and c_{med} are respectively the maximum and the medium damping coefficient provided by the damper. Considering that high torque values are required only for few fractions of a second, it is possible to state that the value of c_{med} coincides with the minimum damping value c_{min} provided by the damper. Then the equation (4) can be rewritten in this way:

$$\begin{Bmatrix} FR_1\text{: Dampen wobble} \\ FR_2\text{: Mantain comfort} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_1\text{: } c_{max} \\ DP_2\text{: } c_{min} \end{Bmatrix} \quad (5)$$

Referring to the model developed by Sharp and Limebeer [8] and considering the data shown in Fig. 2, it is possible to determine the limit values of the damping coefficient that can guarantee both safety (wobble dampening) and riding comfort (soft steering). Since, according to [8], the damping value of about 7 Nms/rad is able to ensure the wobble dampening in the whole speed range of the motorcycle, c_{max} is set greater than or equal to 7 Nms/rad. On the other hand, in order to obtain a soft steering in normal conditions, c_{min} is set less than or equal to 0.9 Nms/rad.

Considering that these values are really important in the design of the steering damper, it is possible to put these conditions as constraints within the Axiomatic Design. Other important constraints relate to the integration of the steering damper into the steering tube, which puts some limits on the external dimensions of the damper. The height h and outer diameter D_E of a standard steering tube, whose typical values vary respectively from 120 to 180 mm and from 50 to 80 mm, have been considered as constraints for the Axiomatic Design. Table 1 sums up the design constraints below:

Table 1. Axiomatic Design constraints.

Constraint (CSTR)	Condition
CSTR1	$c_{max} \geq 7\ Nms/rad$
CSTR2	$c_{min} \leq 0.9\ Nms/rad$
CSTR3	$h \leq 180\ mm$
CSTR4	$DE \leq 80\ mm$

Equation (5) and Table 1 complete the Axiomatic Design modeling. So, according to Axiomatic Design, it is necessary to design a steering damper with variable damping in order to meet the customer needs of both safety and comfort and to fully integrate it into the steering head of a motorcycle in order to optimize the system efficiency.
An analysis of the state of the art of rotary dampers shows how the use of MR fluids could be a key factor to obtain variable damping characteristics [12,13].

4. An innovative steering damper based on MR fluid

According to Axiomatic Design and following equation (5) and the design constraints shown in Table 1, a conceptual solution of a steering damper with variable damping and fully integrated into the motorcycles steering tube has been found, in order to meet the customer needs of both safety and comfort and optimize the system efficiency. This paper proposes a concept of a steering damper based on MR fluid and fully integrated into the steering tube, able to generate the required torque values. A conceptual scheme is described in Fig. 4, where it is shown a damper section orthogonal to the steering axis δ.

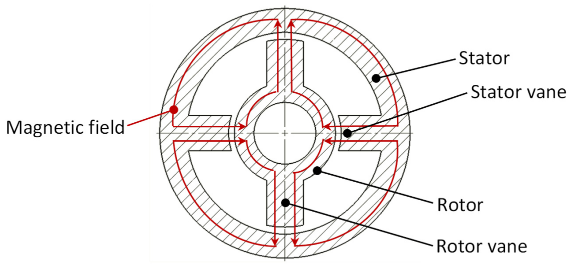

Fig. 4. Conceptual scheme of the MR damper.

As shown in Fig. 4, the damper is characterized by two main parts: a fixed component (or stator) and a rotary component (or rotor). Said components enclose a volume between them, that is filled by a MR fluid. Both the stator and the rotor have a pair of vanes, diametrically opposite, along their whole axial length, dividing the volume in four chambers. The chambers are so separated by four meatuses of fluid.

The novel conceptual idea is to make the stator coincide with the steering tube of the motorcycle and the rotor with the steering shaft. This solution achieves a full integration of the damper in the steering tube. Moreover, in this way the reduced space available in the radial direction is compensated by a relevant axial extent of the device, in order to generate adequate torque values.

Some electromagnets, or coils, are housed on the vanes of the stator and/or the rotor in order to generate a magnetic field across the meatuses. In this way the magnetic field direction is orthogonal to the liquid flow: this is the optimal condition to maximize the increase of the fluid viscosity and therefore minimize the intensity of the magnetic field required to achieve the scope.

From the conceptual solution found with the Axiomatic Design approach, a full dimensioning of the steering damper has been developed later through numerical and FEM analyses, as well described in [14-16].

The dimensioning was set trying to optimize both the intensity of the magnetic field and the amount of torque produced by the damper. In particular, the optimization consists of minimizing the damping torque without the magnetic field and maximizing it when the magnetic field is applied [16].

The external dimensions of the stator found for the optimal configuration are shown in Table 2, where *h* is the axial size of the stator along the steering axis and D_E is the outer diameter [16]:

Table 2. External dimensions of the stator in the optimal configuration.

Characteristic dimension	Optimized value (mm)
h	150
D_E	73

As shown in Table 2, the total integration of the damper into the steering head of the motorcycles properly meets the $CSTR_3$ and $CSTR_4$ (see Table 1), since the external size of the stator is clearly compatible with a standard steering tube size.

In addition, the torque curves of the MR damper as a function of the steering angular speed in the wobble range were obtained through further numerical analyses of the device in the optimal configuration, with the application of the magnetic field (“H on”) and without magnetic field (“H off”, see Fig. 5) [16]. In Fig. 5 the areas of the graph highlighted represent the acceptable ranges of the damping values for FR_1 (green zone) and for FR_2 (blue zone).

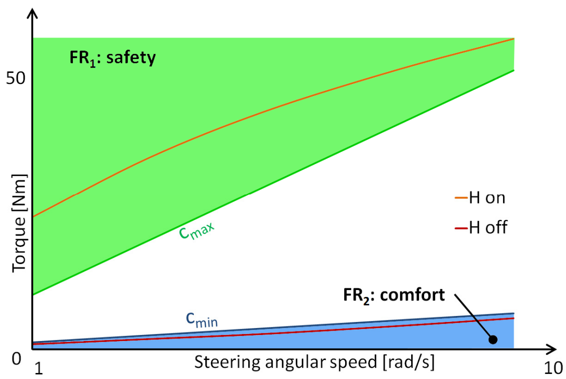

Fig. 5. Torque curves of the MR steering damper.

Analyzing the results shown in Fig. 5, it is possible to state that the steering damper meets both the FRs in the whole steering speed range (referred to the wobble mode) and that the torque values provided by the steering damper fully meet the Axiomatic Design constraints ($CSTR_1$ and $CSTR_2$).

5. Evaluation of the information content of the MR damper vs. traditional dampers

The information content, i.e. the probability not to satisfy the required damping values in every riding condition, has been evaluated for both the MR damper and the traditional dampers.

As mentioned in section 3, the greatest difficulty for the standard steering dampers is to meet both the functional requirements of safety and comfort.

A low damping coefficient is in fact able to satisfy the comfort conditions (FR_2), but can’t meet the safety functional requirement. A high damping coefficient instead fully meets the safety requirement since it is able to dampen the wobble in the whole vehicle speed range, but can not ensure a comfortable riding.

Fig. 6 shows the damping coefficient range of the MR damper compared to the required range of both FRs.

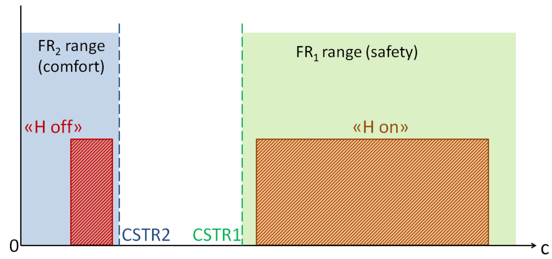

Fig. 6. Damping coefficient range of the MR damper compared to the FRs required range.

As shown in Fig. 6, the MR damper meets both the functional requirements of safety and comfort, since it is able to switch from the minimum damping coefficient (c_{min}) to the maximum one (c_{max}) simply by applying the magnetic field H. In this way the MR damper information content is minimized, according to the Information Axiom.

Conclusions

This work illustrates the utility of Axiomatic Design theory as a tool for innovation. It has been shown that motorcycle steering dampers are characterized by two functional requirements (FRs): the functional requirement of safety, that requires a high damping coefficient, and the functional requirement of comfort, that requires a low damping coefficient.

The traditional steering dampers with constant damping coefficient have less number of DPs than FRs (coupling), and hence it is impossible to satisfy the two FRs at the same time. In order to define the damping coefficients generally required on the steering axis to ensure safety and comfort in all conditions, a model of motorcycle developed by Sharp and and Limebeer has been considered [8].

By following the Axiomatic Design principles, it was possible to find an innovative conceptual solution for a steering damper based on MR fluid with a decoupled design matrix. This new steering meets both the functional requirements of safety and comfort, since it is able to switch from the minimum damping coefficient (c_{min}) to the maximum one (c_{max}) simply by applying a magnetic field. In this way, unlike the traditional steering dampers, the MR damper information content is minimized, according to the Information Axiom.

Another great advantage of the new MR damper compared to the traditional dampers is that it can be housed in the motorcycles steering tube, resulting in a very high efficiency and integration. Regarding motorbikes, the damper is able to stop the wobble oscillations at high speeds while still providing the right steering softness in the normal riding conditions. Regarding scooters, the damper is able to provide a soft steering in the traffic, in order to maintain a high comfort level, and to eventually dampen the wobble in case it occurs at sustained speed, since in the last few years the scooters performance is getting higher and higher.

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