

Electronic Stability Control of a Narrow Tilting Vehicle

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ABSTRACT

This paper aims to contribute to the development of an electronic stability control for narrow, fully tilting vehicles with handling and stability characteristics similar to motorcycles, and to improve the understanding of the driver-vehicle interaction. To allow for high energy efficiency of the control system, mainly steering torque is applied to stabilize and tilt the vehicle. The dynamic properties of the specific investigated vehicle suggest high demands to a driver without an appropriate control system. To allow for automobile-like operation of the steering wheel, the motion of the steering wheel and the steering system of the front wheel has been decoupled, and a steer-by-wire system has been developed. Both simulations and field tests with a prototype proved proper performance of the electronic stability control, but also revealed the need of an automobile driver to adapt to this kind of vehicle when operating it even with the control system.

INTRODUCTION

To make energy-efficient lightweight vehicles more attractive to customers, an increasing number of tilting three-wheeled vehicles has been developed. The vehicle dynamics of different narrow tilting three-wheeler concepts and control strategies are investigated e.g. with non-tilting rear assembly in [1, 2, 3] or for small tilting vehicles in [4, 5]. The driving characteristics of vehicles with non-tilting rear assembly are typically expected by the driver to be similar to those of automobiles, thus the driver does not care about vehicle stability with respect to tip-over, and active systems have to allow for appropriate tilting of the front assembly (including the passenger). However, high tilting energy is required to move the passenger cabin with respect to the non-tilting rear assembly. Hence, energy efficiency of these systems is poor.

Small tilting vehicles are designed to behave and to be perceived by the driver to be similar to a motorcycle, and no active systems are needed.

In this paper, an electronic stability control for a narrow tilting large-sized three-wheeled vehicle [6] will be presented and characteristic properties of the uncontrolled and controlled vehicle will be discussed. The proposed control will both stabilize the motion of the vehicle and tilt the full vehicle by applying mainly steering torques similar to motorcycles to guarantee energy efficiency of the system. The proposed electronic stability control was successfully tested on a prototype.

In the subsequent Section 2, the narrow three-wheeled tilting vehicle and the corresponding model are described briefly, and characteristic properties are explained. The electronic stability control is addressed in Section 3, numerical results of closed-loop simulations are presented in Section 4. Finally, in Section 5 conclusions are drawn and a further outlook is given.

TILTING VEHICLE

In this paper, a narrow, fully-tilting, three-wheeler with one front and two rear wheels is investigated. When travelling at low velocities, the three-point support of the vehicle may be used to avoid tip-over, while at higher velocities the vehicle is tilted by front wheel steering inputs only, to sustain energy efficiency.

A telescopic fork, similar to those of motorcycles, is considered as front suspension. To allow for fully tilting the vehicle, more complex kinematics of the rear suspension are required to support the rear wheels, [Figure 1](#). These kinematics minimize the difference of the wheel loads of the two rear wheels. The rear wheels are mounted to wheel

carriers, that are pivoted to the chassis to allow a swinging motion each with respect to the chassis (like rear swinging forks of motorcycles) for tilting the vehicle. Further, they are connected by a swinging arm to each other and to an additional suspension frame, which is also pivoted to the chassis. Therewith, a swinging motion of one wheel carrier causes the other wheel carrier to swing in the opposite direction, and thus fully tilting is realized. Moreover, a uniform swinging motion of both wheel carriers causes the additional suspension subframe to swing with respect to the chassis suspended by a shock strut. A detailed description of the kinematics of this vehicle is given in [6]. The mass of the vehicle (including a passenger) is about 600 kg, its track width at upright position is 0.8 m and the wheel base is 2.7 m.

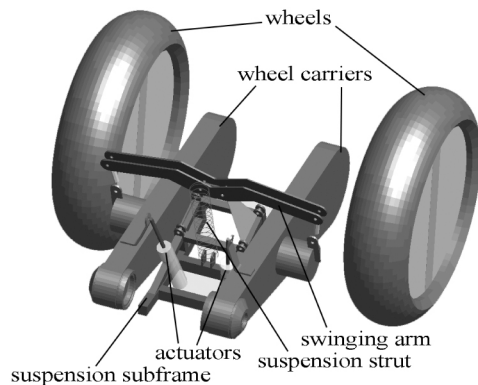


Figure 1. Schema of the rear suspension, [6].

VEHICLE MODELLING

A schema of the MBS vehicle model is presented in Figure 2. It is developed using the commercial multibody system (MBS) program package Simpack [7]. All bodies of the three-wheeler are assumed to be rigid and structural flexibilities are considered with respect to degree of freedom, stiffness and damping. In addition to the above described rear suspension kinematics, actuators are implemented into the rear suspension model to utilize the three-point support at low speeds. Bump stops are modeled at the rear suspension, which constrain the tilt angle to 35° from upright position. Steering torque input is applied using a steering actuator that acts between the chassis and the front fork. For simulation purpose, a simple speed controller is integrated into the model to allow tracking a desired speed profile. The ‘Magic Formula’ motorcycle tyre description including transient tyre behaviour [8] is used to model the road-tyre interaction. The degree of freedom of the vehicle model is 14. For more details on the vehicle modelling please refer to [6].

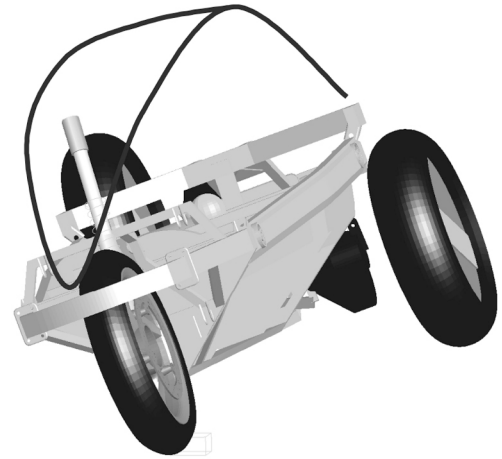
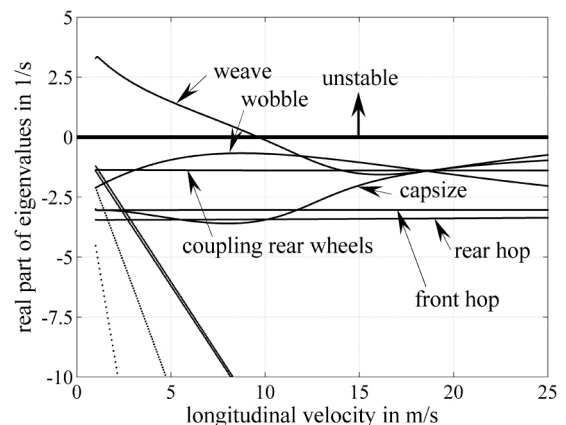


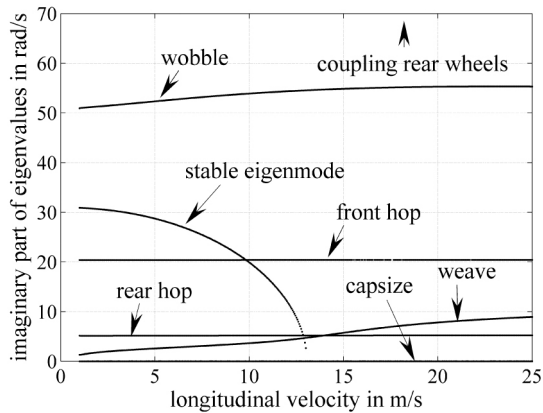
Figure 2. MBS model of the tilting three-wheeled vehicle.

CHARACTERISTIC PROPERTIES OF THE THREE-WHEELER

To get insight into the characteristics of the vehicle, the MBS model of the three-wheeler was linearized with respect to straight running at velocities up to 25 m/s. Calculating and plotting the eigenvalues of the resulting system matrices yields the stability map of the vehicle at straight running, Figure 3. Computing the respective eigenvectors, the well-known motorcycle modes ‘weave’, ‘wobble’ and ‘capsize’ can be identified, see e.g. [8], besides modes resulting from the suspension system (rear hop, front hop, coupling rear wheels). It can be concluded that the vehicle's stability properties are similar to those of motorcycles, and that the weave mode is unstable up to velocities of about 10 m/s. Considering the frequency of the weave mode within the unstable regime, Figure 3(b), a skilled driver may stabilize the steady-state motion of the vehicle. However, to make driving the vehicle more safe and comfortable, an electronic stability system is required to take over this task.



a. real part of eigenvalue at straight running.



b. imaginary part of eigenvalue at straight running.

Figure 3. Eigenvalues of the system matrix of the MBS vehicle model, linearized with respect to the straight rectilinear motion at different speeds.

In Figure 4, the yaw rate response of the vehicle to a steering torque input sweep from 0.1 to 1 Hz with a constant amplitude of 1 Nm is presented. The velocity of the vehicle is set to 20 m/s to avoid unstable vehicle behaviour, see Figure 3. With increasing frequency, the phase lag raises from -40° to -120° . Thus, a driver or a control system faces demanding challenges. After an initial drop, the magnification of the amplitude increases with increasing frequency.

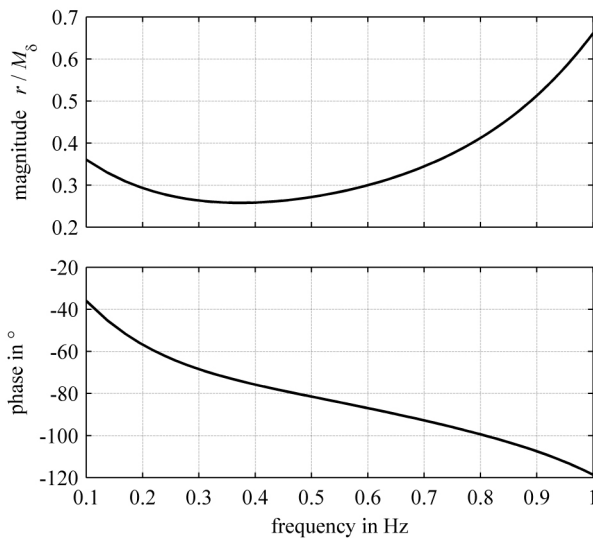


Figure 4. Yaw rate response to steering torque input sweep with amplitude of $M_\delta = 1$ Nm at $u = 20$ m/s.

The open loop response of the three-wheeler to a unit step steering torque input of -1 Nm is shown in Figure 5. The vehicle speed is set again to 20 m/s, to avoid unstable behaviour. The unit step is applied at 1 s. The cornering event is initiated with counter steering (steering angle of the front wheel), indicating a non-minimum phase system (similar to motorcycles). The transient behaviour is characterized by a

damped oscillation of approximately 1 Hz that corresponds to the weave mode, see Figure 3. Due to counter steering, the yaw rate shows initially also negative values, and the lateral velocity changes sign too. The tilt angle of the three-wheeler tends directly towards the steady-state value, indicating minimum phase transfer behaviour with respect to the steering torque input.

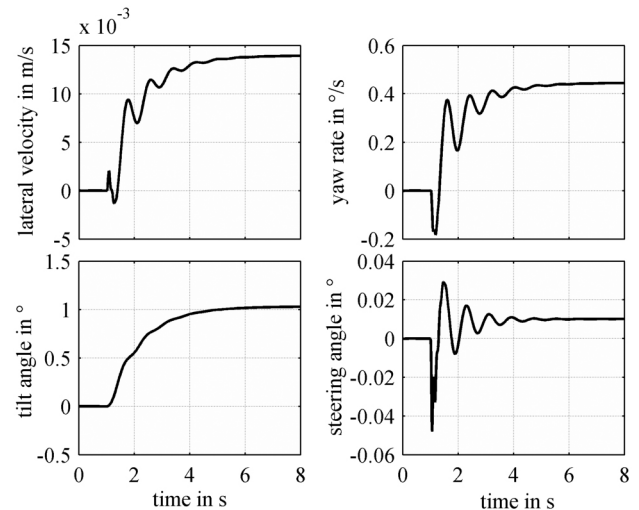


Figure 5. Open-loop step response of MBS vehicle model to step input $M_\delta = -1$ Nm at $u = 20$ m/s: lateral velocity, yaw rate, tilt angle and steering angle of front wheel.

ELECTRONIC STABILITY CONTROL

Considering the open-loop properties of the tilting vehicle, an electronic stability control should facilitate safe and comfortable operation by an average driver. To further allow for automobile-like steering, the steering wheel angle and the front wheel steering angle need to be decoupled. However, the phase lags of the yaw rate response to the steering torque inputs already indicate the need for some adaptation by driver to the specific vehicle behavior.

A basic block diagram of an appropriate control is presented in Figure 6. The steering angle δ_s of the driver's hand wheel is chosen here to be proportional to the tilt angle of the vehicle demanded by the driver, φ_d . The tilt angle φ_d is the reference value to be attained by the controller by applying a steering torque M_δ about the steering axis of the front wheel, using the STC-level, or by applying a 'roll torque' M_φ to the rear suspension, using DTC-level, or by combining both of them. For the sake of energy efficiency, steering torque is applied exclusively at vehicle speeds higher than 3 m/s. At lower speeds, roll torque is applied to avoid fall/tip-over of the tilting vehicle. The system state $\underline{x}$ (see below) as well as the longitudinal velocity u is fed back to the controllers. The mutual influence of both control levels when operating the vehicle with blended inputs can be regarded within the