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Multibody modeling of an electric kick scooter for vertical dynamics

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Abstract. The growing emphasis on environmental sustainability and urban mobility has driven a global rise in the adoption of electric micro-vehicles. Among these, electric kick scooters have emerged as a leading choice, owing to their ease of integration into existing public transportation networks and widespread availability through shared mobility services. As a new transport mode, the scientific community has recently focused on this vehicle category to address regulations and enhance safety and comfort aspects. This study presents the development and experimental validation of a multibody model of an e-scooter and its rider, specifically tailored for ride comfort analysis. The model, implemented in MATLAB/Simscape Multibody, includes a detailed representation of a commercial electric scooter and integrates a custom tire–road contact subsystem, suitable for vertical dynamics. Special emphasis is also placed on the rider model, where a torque-based control strategy of the joints is introduced to replicate the human body's biomechanical response to external inputs. Experimental validation is carried out through on-road tests, consisting of riding at constant speed over a bike path with speed bumps while recording acceleration data. The results highlight the significant impact of the rider on the vertical dynamics of the scooter and demonstrate the importance of incorporating a detailed tire model to accurately capture the interaction with road irregularities.

Keywords: Electric micro-vehicles, Personal urban mobility, Vertical vehicle Dynamics, Vibrations, Ride comfort.

1 Introduction

The growing popularity of electric kick scooters (e-scooters) as affordable, eco-friendly, and lightweight vehicles has placed them at the center of urban mobility discussions [1]. Their widespread adoption is driven by the global trend toward sustainable transportation and the development of shared mobility services [2]. Among electric micro-vehicles (e-MVs), e–scooters stand out for their compact design and ease of integration into existing urban transport systems.

Unlike traditional bicycles or mopeds, e-scooters feature an upright riding posture, small wheels, and low vehicle mass. These characteristics significantly affect their maneuverability, stability, and dynamic response [3]. Notably, due to the relatively low

weight of the vehicle, the rider's inertia plays a predominant role in the overall system dynamics. As a result, accurate analysis of the rider-vehicle interaction is crucial, particularly for studying handling and comfort.

These peculiarities have increasingly attracted the attention of the scientific community. Several experimental studies have investigated the vibration exposure of e-scooter riders in real scenarios [4, 5], exploiting statistical analysis on riders [6] or operational modal analysis [7].

In this context, multibody modelling constitutes a powerful tool for gaining a deeper understanding of the dynamics of complex systems. Many authors have employed numerical simulations to investigate the rider influence in different riding scenarios. For instance, a detailed e-scooter/rider model is used to demonstrate the influence of the rider motion on vehicle longitudinal dynamics during an emergency braking maneuver [8]. As for vertical dynamics, a simplified model is proposed in [9] to study the response to small bumps while a multibody approach for ride comfort assessment is presented in [10] for different speeds, road qualities and suspension layouts. Regarding lateral dynamics, a stability analysis is conducted linearizing a multibody system, highlighting the influence of vehicle and tire characteristics [11].

The purpose of this research is to develop and experimental validate a multibody model of an e-scooter coupled with a rider specifically designed for vertical dynamics and ride comfort. To achieve this goal, a multibody model is developed in MATLAB/Simscape, considering a commercial vehicle under real operating conditions. The model of the vehicle is equipped with a custom tire–ground contact module accounting for the non–linear radial reaction force and the envelope effect.

A torque-based control strategy is applied to the joints of the rider considering both gravity and the response to inputs from the vehicle. For the model validation, an experimental campaign is conducted by driving the e-scooter at constant speed over seven regularly spaced speed bumps. During the tests, accelerations and the angular speed of the rear wheels are recorded.

The article is organized as follows. First, the multibody system is described focusing on both vehicle and rider. Then, the on-road testing is presented, highlighting sensors setup, testing procedure and data processing. Finally, experimental and numerical results are presented and discussed.

2 Modelling

The multibody model is developed in MATLAB/Simscape Multibody environment and consists of two main sub-systems, i.e. the vehicle and the rider.

2.1 Electric kick scooter

The multibody system of the vehicle, illustrated in **Fig. 1**, is composed of three subsystems, each consisting of several rigid bodies: the chassis (including the deck, steering column, and mudguards), the front assembly (wheel motor and tire) and the rear assembly (rim, braking system, and tire).

The chassis is connected to the front and rear assemblies by two kinematic revolute joints. Since the simulated maneuver involves only longitudinal and vertical dynamics, the steering column is rigidly constrained to the deck. Additionally, lateral translation (along the y axis), lean rotation (around the x axis), and yaw rotation (around the z axis) are constrained using a kinematic planar joint between the deck and the ground. This final configuration consists of five Degrees of Freedom (DoFs), i.e., the in–plane motion of the chassis (translations along x and z axes and rotation around y axis) and the rotations of the front and rear wheels.

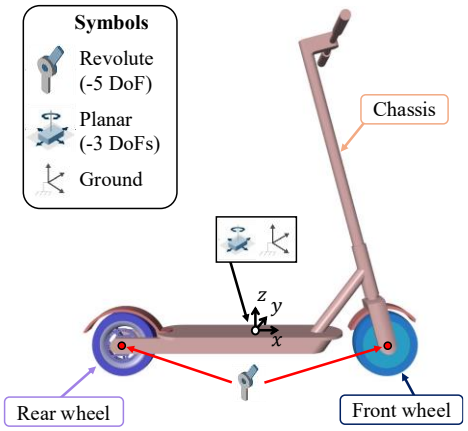


Fig. 1. E-scooter multibody model.

To simulate tire–ground interaction, a custom contact module is developed in MATLAB/Simulink and integrated into the simulation loop, as depicted in **Fig. 2**. The inputs to the contact subsystem are the position ($\boldsymbol{p}_{f/r}$) and the orientation ($\boldsymbol{\theta}_{f/r}$) of the front wheels coming from the multibody system as well as the road profile $z_R(x_R, y_R)$. The equivalent road elevation at the front and rear, $z_{e,f}$ and $z_{e,r}$, is computed as the average of the elevations n nodes within the respective contact patch areas on the road profile. The vertical force $F_{z,f/r}$ is then calculated based on the tire radial deflection $d_{t,f/r}$, defined as the difference between the actual vertical position of the wheel and the equivalent road elevation. This force is fed back into the multibody system and used to update the footprint dimensions dynamically. Both the vertical force and the footprint dimensions are experimentally characterized as functions of the radial tire deflection and used to parametrize the model. Simulations are performed adopting the variable step *ode23t* solver, which is suitable for moderately stiff multibody systems.

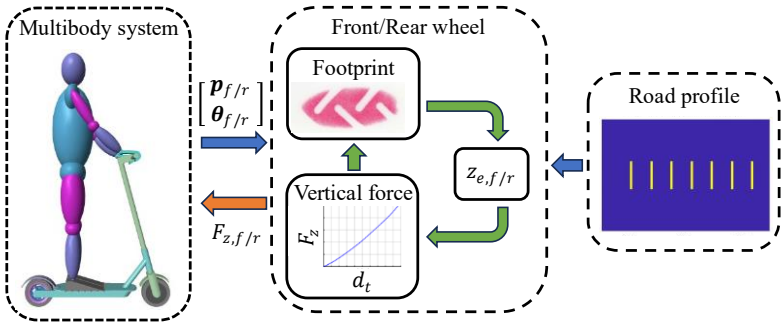


Fig. 2. Integration scheme of the contact module in the multibody system.

2.2 Rider

The rider model, illustrated in **Fig. 3**, consists of 14 rigid bodies (head, trunk, right and left arms, forearms, hands, thighs, shanks, and feet) connected by 13 kinematic joints, including the neck, right and left shoulders, elbows, wrists, hips, knees and ankles. All segment dimensions and densities are defined parametrically to accurately reproduce the geometry and inertial properties of the actual rider.

When considered as a standalone system, the rider model features a total of 37 DoFs. The interface between the vehicle and the rider is modeled through two kinematic revolute joints that connect the rider's hands to the e-scooter's steering handlebar, and two lumped contact forces that represent the interactions between the soles of the rider's shoes and the deck floor.

Each DoF of the rider's joints is actuated using a torque-based control strategy comprising two contributions: a static torque to maintain the desired posture under gravity, and a dynamic torque to compensate for the inertial effects induced by the vehicle maneuver.

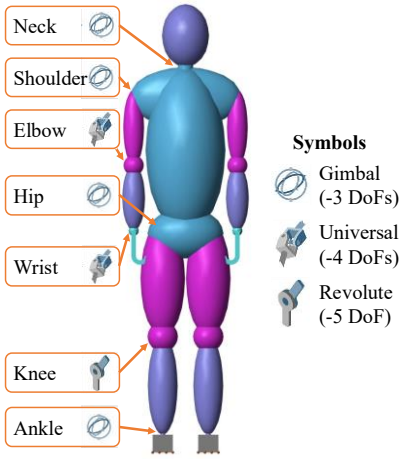


Fig. 3. Rider multibody model.

3 Experimental validation and results

3.1 Sensor setup and test procedure

Fig. 4 shows the sensors setup (left), and the tested road (right) used during the experimental campaign. The acquisition system, a Siemens SCADAS XS, is housed in a plastic case mounted on the steering column. Accelerations at the front and rear wheels are measured using two tri-axial IEPE Kistler accelerometers, with a sampling frequency of 3200 Hz. An inductive tachometer is installed on the rear wheel to monitor its angular velocity.

The experimental test consists of driving at constant velocity of approximately 25 km/h along a bike path featuring seven speed bumps, each with a height of 4.5 mm and spaced 0.65 m apart. The test is performed five times to assess repeatability of the results. The recorded acceleration signals are filtered using a low pass filter with a cut–off frequency of 100 Hz to reduce the experimental noise. Time histories are isolated at the location of the bumps for the numerical comparison and model validation.

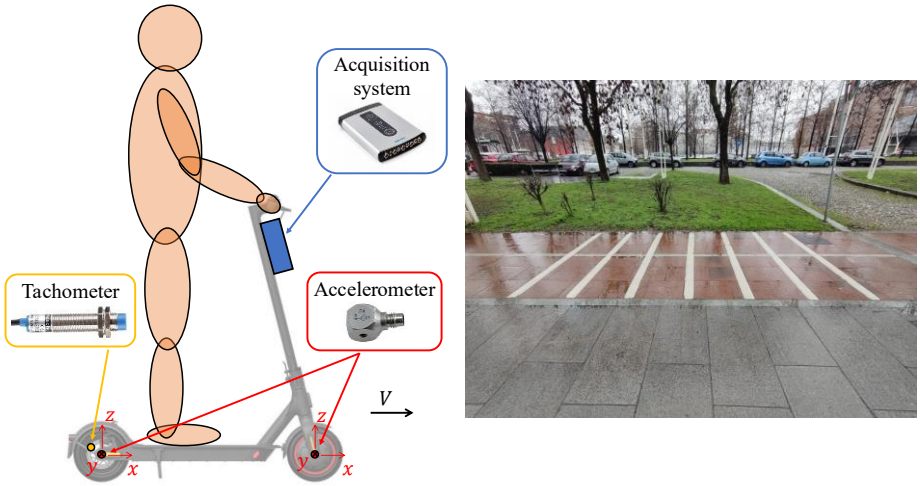


Fig. 4. Sensor setup (left) and test track (right).

3.2 Experimental-numerical comparison

Fig. 5 shows the comparison between the experimental (black line) and the numerical (orange line) acceleration along the z-axis at the front and rear wheels. Overall, the multibody model accurately captures the peak positive and negative accelerations (8.2 g and -6.5 g at the front wheel, 11.6 g and -9.6 g at the rear wheel) with minor discrepancies. At the front wheel, high-frequency dynamics are less prominent in the simulation, possibly reflecting a simplified representation of the rider's dynamic response. Conversely, the rear wheel acceleration closely follows the experimental trend, with

small differences potentially attributable to vehicle velocity fluctuations not reproduced in simulation.

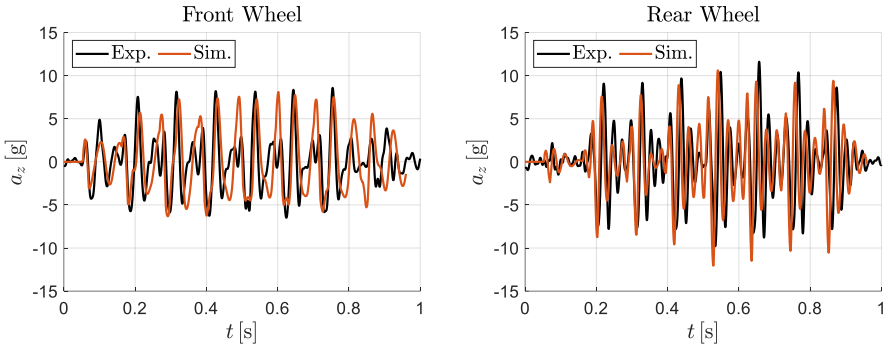


Fig. 5. Experimental-numerical comparison of the acceleration along z-axis of the front (left) and rear (right) wheels.

4 Conclusions

This research investigates the vibrations occurring on an electric kick scooter under real operating conditions. In this first phase, a multibody model comprising both a commercial vehicle and a rider has been developed to simulate the riding motion over a bike path with a series of bumps at constant speed. A custom tire–ground contact module has been successfully developed and integrated in the simulation framework, accurately accounting for the radial stiffness and envelope effect of the tire. The model has been validated through the comparison of numerical and experimental accelerations measured at the wheel centers, showing good agreement. These results demonstrate the effectiveness of the model in representing the dynamics of the e–scooter/rider system and its potential to support vehicle performance optimization.

Future developments will extend the analysis to a wider range of riding conditions, including variable speeds and uneven road surfaces, to better characterize the rider's dynamic response and further enhance the model's predictive capabilities.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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