Dynamic Characterization of an Electric Kick Scooter Through Operational Modal Analysis

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Abstract. In recent years, the urban mobility framework has been characterized by the increasing spread of electric micro-vehicles, aiming at mitigating pollution and traffic congestion in major city centers. Among these vehicles, electric kick scooters have gained popularity due to their seamless integration into existing urban mobility systems through sharing services. The dynamic response of these two-wheeled vehicles is highly influenced by the driver's position and intrinsic body flexibility, which vary according to operative conditions. The objective of this research is to identify the modal parameters of a commercial electric kick scooter through operational modal analysis in real driving conditions. An experimental campaign is conducted driving an e-scooter on various surfaces and monitoring accelerations at different points of the vehicle. The vehicle is driven on asphalt and pavé surfaces at several velocities to test different road excitations. Signals collected during these tests are processed in LMS Testlab tool to identify natural frequencies and mode shapes of the system up to 100 Hz. The analysis reveals four macro-groups of mode shapes that characterize the modal behavior of the structure involving the steering joint, the pitch of the entire system, and the compliance of the deck.

Keywords: Electric standing scooter, Personal urban mobility, Light vehicle, Ride comfort, Vibration analysis, Experimental acquisitions.

1 Introduction

In the last years, urban mobility has experienced a notable surge in the adoption of micro-electric vehicles [1]. The imperative to mitigate pollution and alleviate traffic congestion on urban streets has prompted governments to actively promote the purchase of personal micro-vehicles and their utilization in shared mobility services. Electric kick scooters (e-scooters) have emerged as a popular solution in this evolving vehicle category driven by their compact size, light weight, and cost-effectiveness [2]. These characteristics make e-scooters considerably appealing for road users, especially for short urban journeys, as they can be easily integrated into existing public transport systems, smoothing the so called “last-mile gap” issue [3].

The recent proliferation of e-scooters has spurred scientific interest in enhancing the knowledge of their vehicle dynamics. Due to intrinsic differences compared to other micro-electric vehicles, specific analyses are required. In particular, the standing position of the rider sets e-scooters apart from traditional bikes and motorcycles. Additionally, the higher inertia of the rider compared to the inertia of the vehicle represents a notable departure from the dynamics of typical motorized two-wheeled vehicles. The main research topics aiming at improving the ride experience on e-scooters are related to comfort, safety and rider's driving habits. Given the limited availability of reliable bibliographic sources on e-scooters, electric bikes (e-bikes) are often used as benchmark. A vibrational comparison between e-scooters and e-bikes was proposed by Ventura and Boglietti [4, 5]. Asperti et al. presented a validated lumped parameter model including the rider's mechanical impedance to analyze ride comfort and road holding capability on lumped obstacles [6] and random irregularities [7]. Cano et al. conducted an experimental assessment on vibrations perceived by the rider driving at different velocities on asphalt and pavé roads [8]; the effect of vehicle velocity and front suspension stiffness is shown by the same authors through a simplified multibody model [9]. Many research activities have been conducted on risky conditions for accidents, related to vehicle stalling, loose of stability or emergency braking. The influence of tire size and rider's mass driving on curb traversing was investigated by Arslan et al. through a simplified multibody model [10]. E-scooters were compared to bikes by Paudel in terms of self-stability and steady-state turning performance, highlighting the impact of rider's posture, tire size and longitudinal acceleration [11]. The longitudinal performance was investigated by Vella et al. conducting an experimental campaign [12] and showing the influence of rider's reaction in braking conditions through a passive multibody model of the rider [13]. The advances on micro electro-mechanical systems have recently allowed the adoption of wearable technologies (MIMUs) for tracking human motion in various contexts, including on-road tests of e-scooters. The kinematics of the human body was experimentally analyzed on several subjects reproducing realistic maneuvers by Garman [14]. A non-parametrical statistical analysis based on a population of 14 riders was conducted on vehicle-human body transmissibility, driving on speed bumps at different constant velocities [15].

Based on the above-mentioned literature review, a deep understanding of e-scooter dynamics requires to consider the full system constituted of vehicle and rider. For this reason, conducting laboratory tests under stationary conditions can be quite complex and Operational Modal Analysis (OMA) is a potential tool for this analysis. This output-only method has been largely exploited in very different applications where on-field tests are required to consider both the modal behaviour of the mechanical system and its operative conditions, e.g., the angular speed for a rotating machine or the driver for the e-scooter in this application. Operational modal analysis is a technique widely employed in the field of ground vehicles with the target of reducing vibrations and noise [16]. The sources of vibrations in a transmission of a passenger car were experimentally investigated by Abreu [17]. Hassen et al. reconstructed the modal behaviour of a half car model by OMA and compared the results with the traditional modal analysis [18]. The performance of different suspension architectures is assessed by Soria et al. [19].

Operative deformation in specific working conditions was studied by Bonisoli et al. to develop a method for detecting critical mode-shapes in motorbike components [20, 21].

The target of this research activity is to analyze the modal behaviour of the system composed by a commercial electric kick scooter and its rider in real driving condition through operational modal analysis. Vehicle accelerations are synchronously acquired in different points of the vehicle driving on asphalt and pavé road surfaces at several constant velocities. The experimental signals are post-processed in LMS Test.Lab for the identification of the modal parameters of the system.

The paper is structured as follows. The second paragraph provides a description of the experimental campaign, with a focus on the sensor setup, the testing protocol, and the signal processing. The third section outlines the main modal parameters, and their comparison in the different testing conditions. In the fourth section, the main conclusions are drawn and the current efforts in the presented research activity are provided.

2 Experimental tests

All the experimental tests are conducted by a single rider driving the same commercial vehicle. The rider is a young and healthy male, and his main characteristics are reported in Table 1.

Table 1. Characteristics of the rider.

Characteristic	Value
Weight [kg]	76
Height [m]	1.80
Body Mass Index (BMI) [kg/m^2]	23.5
Age [year]	27

Both the dominant hand and foot of the rider are the right ones. Moreover, the rider has good experience in driving light two-wheeled electric vehicles.

The e-scooter under analysis is equipped with an electric motor mounted in the front wheel (nominal power of 300 W) and a battery pack included in the deck (voltage of 36 V, capacity of 12.4 Ah). No suspension system is mounted at the front and at the rear and the tires have an 8.5 inch diameter with a nominal inflation pressure of 3.5 bar. The unladen mass of the vehicle is equal to 14.4 kg. The maximum vehicle velocity is electronically limited to 25 km/h.

2.1 Sensor setup

The sensor setup used during the whole experimental campaign is depicted in Fig. 1.

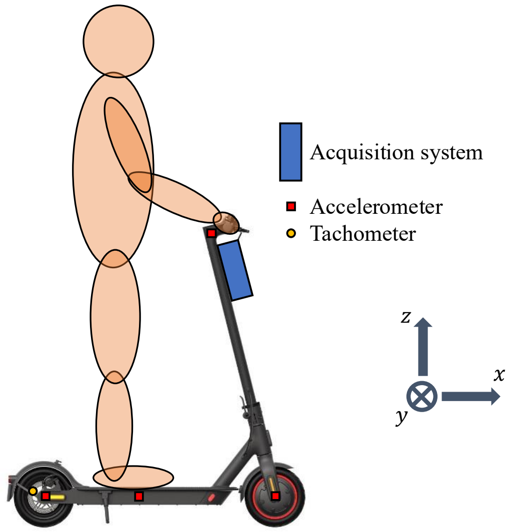

Fig. 1. Sensor setup.

Siemens SCADAS XS is used as acquisition system; it is placed in a plastic case fixed to the handlebar and the steering column of the vehicle. Four IEPE Kiestler tri-axial accelerometers are used to acquire the vibrations of the vehicle (acceleration range equal to ± 50 g, theoretical sensitivity of 100 mV/g, linear frequency response between 1 and 5000 Hz). The location of the four accelerometers derives from other research activities conducted in parallel on the same vehicle aiming at characterizing ride comfort. Two accelerometers are placed in correspondence of the front and rear wheel centers with the purpose of evaluating the vibration input from the road surface, filtered only by the tires. Two accelerometers are placed as close as possible to the interface between the human body and the vibration source as prescribed by ISO 2631-1 [22] and ISO 5349-1 [23], i.e., on the deck floor and the hand grip; a good compromise between optimal sensor positioning and driving safety leads to place one accelerometer on the lateral side of the deck (under the feet) and the other one at the middle of the handlebar. Vehicle vibrations are acquired with a sampling frequency of 3200 Hz.

Gebildet inductive proximity sensor (maximum detection distance equal to 4 mm) is readapted as tachometer for the measurement of the angular velocity of the rear wheel. The proximity sensor is clamped to the e-scooters frame and bolts are fixed on the five spokes of the rear wheel to trigger the analogue signal: the sensor is powered by a 7.3 V LiPo battery.

2.2 Test procedure and signal processing

The experimental tests are conducted on two different road surfaces, a 320 m long asphalt road and a 100 m long pavé road. The road textures are reported in Fig. 2.

Fig. 2. Tested textures: asphalt (on the left) and pavé (on the right).

The e- scooter is driven at several constant velocities (from 5 km/h up to 25 km/h) on a straight-path, steering as little as possible. The acquisition is started and stopped in standstill condition. The vehicle velocity is computed in post-processing using the angular velocity estimated by the proximity sensor and assuming negligible tire slip. The duration of each acquisition depends on the time required to accelerate the vehicle up to the target velocity and on the time necessary to travel the two road segments. The rider is helped to maintain a constant velocity thanks to the cruise control modality. Due to the harsh driving condition, it was not possible to perform tests above 19 km/h on the pavé surface. For sake of simplicity, it is decided to study only three velocities for each road surface (8 km/h, 14 km/h and 19 km/h). For each vibration signal, only the constant velocity phase is considered in the following analyses. The vertical acceleration (z axis) time history of the front wheel is considered as reference signal for the computation of the Cross Power Spectral Densities (CPSD) of the different accelerations. The CPSD corresponding to the acceleration along the lateral axis of the vehicle (y axis) are excluded from the analysis since this research work focuses on the in plane modal behavior of the vehicle (xz plane). The CPSD are then processed with PolyMAX algorithm [24] to identify the modal properties of the system (natural frequencies f_r, damping ratios ζ_r and mode shapes $\mathbf{\Phi}_r$) in the frequency range between 0 and 100 Hz. Considering a model rank of 40, all the stable poles identified in the stabilization diagram are selected for the computation of the corresponding real mode shapes.

3 Results and discussion

From a preliminary analysis of the results from all the selected acquisitions, similar mode shapes are identified in specific frequency ranges. Following this evidence, the mode shapes are grouped in four topological macro-categories. Table 2 refers to the test at 19 km/h on pavé surface and shows for each mode shape the corresponding group, the natural frequency, and the damping ratio. The widest frequency range corresponds to the set of modes from 6 to 10, while the narrowest one is related to modes 11 and 12. Instead, the damping ratio has a big variation for the two groups of modes at lower frequencies. The typical mode shapes for each macro-category, belonging to the same test, are depicted in Fig. 3.

Table 2. Modal properties identified on pavé at 19 km/h.

Mode	Macro-category	Frequency [Hz]	Damping [%]
1	1	4.6	13.2
2		10.1	4.3
3		16.0	2.7
4	2	22.0	9.4
5		27.4	3.3
6		35.7	1.0
7		39.4	2.5
8	3	47.3	1.2
9		52.2	2.0
10		57.9	1.0
11	4	63.7	2.1
12		69.5	2.0

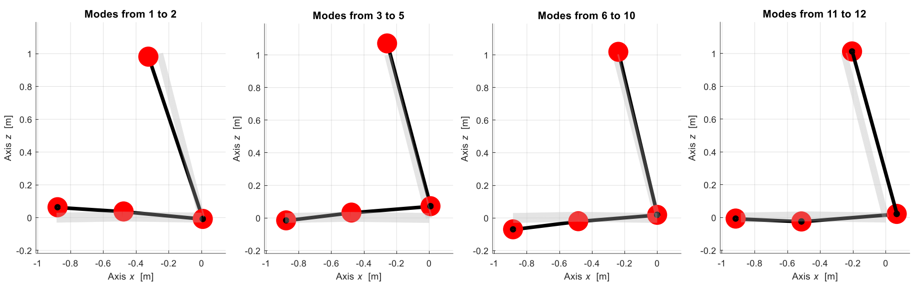

Fig. 3. Mode shapes identified on pavé at 19 km/h and shown in LUPOS environment [25].

The first group of mode shapes seems to correspond to the flexibility of the steering hinge. The second and third group of mode shapes refer to the pitch of the e-scooter: the difference between the two groups stands in the location of the structural node (at the rear part of the vehicle for the second group and at the front of the vehicle for the third group). The higher the frequency, the more the structural node moves forward from the rear to the front wheel. Finally, the fourth group of mode shapes involves the axial and flexural compliance of the deck.

In Figs. 4-5, MAC index [26] is used to evaluate the correlation between mode shapes. MAC is null, when two mode shapes are orthogonal or have very low similarity, while it is 100% when two mode shapes are equal or proportional to each other. Both AutoMAC, i.e., the comparison between a set of mode shapes with the same set, and CrossMAC, i.e., the comparison between two different set of modes, are computed. In particular, the CrossMAC is used to appreciate modal differences when velocity or road surface is changed.

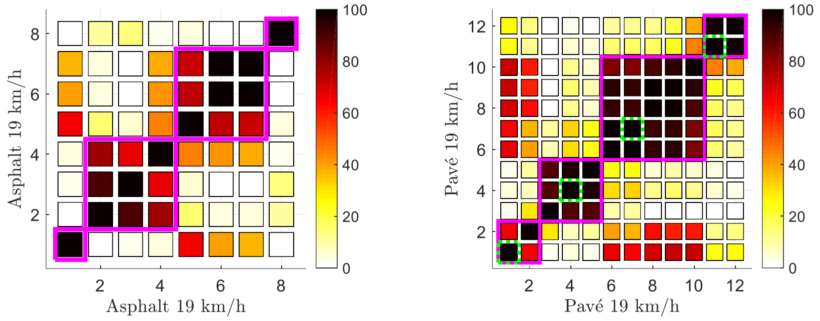

Fig. 4. AutoMAC computed for tests on asphalt (on the left) and pavé (on the right) surfaces, both at 19 km/h.

In both the tests at 19 km/h, the four macro-categories of mode shapes are evident, and they are highlighted in Fig. 4 with magenta contours. Jacobsen proposed to distinguish the real structural modes of a system from the Operational Deflection Shapes (ODS), due to excitation forces exploiting MAC index and the damping ratio [27]. Specifically, similar modes can be grouped based on MAC index and the real mode can be recognized by a higher value of damping ratio within each group. Following these guidelines, one mode shape for each group is selected, and it is green contoured in Fig. 4 on the right. This pattern structure for the MAC matrix is common in all the acquisitions. Similarities between mode shapes far in frequency, i.e., between the first and the third macro-categories of mode shapes, is probably related to low number of sensors used to acquire vibrations on the structure. This means that the pitch modes (from 6th to 10th in Fig. 4 on the right) are also characterized by a relative rotation between the deck and the steering column. The generation of multiple modes may be due to two contributions, i.e., the rider and the tire. As concerns the rider, human body can differently behave during the acquisition time, thus influencing with its inertia and the muscular stiffness of arms and legs the dynamic response of the global system. As regards the tire, its non-constant stiffness can affect the force transmissibility from the ground to the vehicle, generating harmonic components acting on the vehicle sub-system.

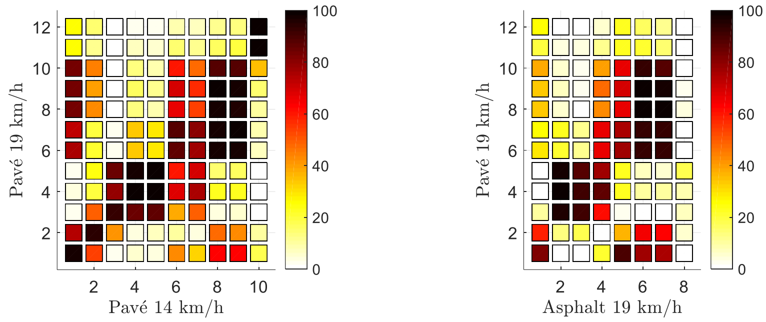

Fig. 5. CrossMAC computed for different velocities on pavé (on the left) and for different road surfaces at the same velocities (on the right).

The comparison of the tests conducted at different velocities, reported as CrossMAC analysis in Fig. 5, underlines the same results in terms of patterns of the mode shapes. The lower the speed, the lower is the number of the identified mode shapes. Similarly, the tests on asphalt surface return a lower number of modes with respect to the tests on pavé surface. The comparison between different road surfaces at 19 km/h (Fig. 5 on the right) shows that there is no correlation between the last macro-groups of modes of each test: indeed the 8^{th} mode in the asphalt seems to correspond to the second flexural mode of the deck (f_8 of 93.6 Hz, ζ_8 equal to 0.6%) and is not identified in the pavé test while modes 11^{th} and 12^{th} of the pavé test correspond to the first bending/axial mixed mode of the deck.

4 Conclusions

In this research work the dynamic behaviour of the system represented by an electric kick scooter and a rider is investigated through operational modal analysis technique. Several tests driving straight at constant velocity on asphalt and pavé surfaces are performed to detect vibrations on characteristic points of the vehicle.

The analysis of the experimental data shows that the main mode shapes related to the vertical dynamics and comfort of the e-scooter can be identified in the frequency range up to 100 Hz. As emerged from the comparative analysis through MAC index, the identification of multiple modes of the same topology can be addressed to several factors, i.e., the dynamic response of the rider and the nonlinear behavior of the tire stiffness.

OMA technique seems effective for identifying the characteristic frequencies of the system but requires a larger number of acquisition nodes for a more accurate identification of the mode shapes.

The authors are working on the development of a numerical model, able to demonstrate that the modal behaviour related to electric kick scooters is dependent on the rider's dynamics. Moreover, future developments of this research activity may be focused on evaluating even the human body response instrumenting also the rider with wearable sensors, involving a large number of subjects and different e-scooters.

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