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CONCEPTUAL DESIGN OF A SMALL-SCALE DYNAMOMETER PROTOTYPE FOR ELECTRIC VEHICLE ANALYSIS

Maria Augusta de Menezes Lourenço
Fabrício Leonardo Silva
Ludmila Correa de Alkmin e Silva
Jony Javorski Eckert
Franco Giuseppe Dedini
Integrated Systems Laboratory (LabSIn), Integrated Systems Department (DSI)
University of Campinas - UNICAMP 200 Mendeleyev Street, Campinas, 13083970, SP, Brazil
m228252@dac.unicamp.br

Abstract. *Chassis dynamometers are widely used in the automotive industry to evaluate vehicle performance. However, its usage brings some challenges, such as increased inertia of components, high costs and time. In this paper, we present a small-scale chassis dynamometer prototype design as an alternative to the ones used in the industry. The main goal of the present work is to describe the first outcomes of a project being carried in the Laboratory for Integrated Systems of Unicamp whose future objective is to further develop its chassis dynamometer for emulating standard/real driving resistances. It will be able to measure rotation and torque and allow us to obtain other parameters such as longitudinal speed, angular and linear accelerations, power and force. This way, it is possible to analyze the performance of a modular electric vehicle prototype. As a result, we present the design requirements, the 3D modeling of the system and its technical specifications of a small chassis dynamometer.*

Keywords: *chassis dynamometer, electric vehicle, small-scale, torque, rotation.*

1. INTRODUCTION

Global warming and increasing caring about the environment stimulate the study and use of electric vehicles (EVs). Moreover, vehicles propelled by internal combustion engines are responsible for a major parcel of pollutant emissions (Yazdani et al., 2015). As emphasized by Corrêa et al. (2015) and Eckert et al. (2018, 2019), the EVs are a promising solution to convert sustainable energy into drive energy, although there are some technological challenges, such as battery costs and charging time.

Furthermore, measuring the performance and efficiency of EVs is a complex task when considering the effects of variable environmental factors (Wager et al., 2014). Working toward the improvement to EV technologies, they have been tested in laboratory benches, such as the modular vehicle platform (hybrid and electric configurations) tested with a chassis dynamometer by Rambaldi et al. (2011).

A dynamometer is a measuring device employed to quantify force, torque and power (Bertoti, 2018). These devices are able to absorb the power output of a machine, which the performance needs to be evaluated (Figliola and Beasley, 2014), and the absorbed power is usually converted to heat or electricity, that is dissipated (Giakoumis, 2017). Therefore, dynamometer benches provide reliable and controlled experimental conditions used by the automotive industry in the development of new technologies (Bertoti et al., 2017).

In rotary machines scenario, it is a measuring instrument connected to the power output of a given rotating machine and it gauges the torque produced by this machine by exerting a resistive torque (Bertoti, 2018). Chassis dynamometers are commonly used to evaluate vehicles and, according to Rambaldi et al. (2011), the test via real cycle's analysis is the only process to exactly define environmental, energy and handling vehicles characteristics and performances. Moreover, several research efforts have utilized chassis dynamometers for the validation of EV and hybrid electric vehicles (HEVs) (Humphries et al. 2016; Mayyas et al., 2017; Gołębiewski and Lisowski, 2018; Beckers et al. 2019).

However, the usage of those equipment and vehicles brings some challenges, such as increased inertia of components, higher equipment costs and time and high quantity components adding uncertainties and noise. Moreover, dynamometer benches require periodical calibration to ensures its accuracy and reliability (Zhao et al, 2013).

In order to simplify the analyses, small-scale prototypes are an alternative and their use has increased. In this way, small-scale chassis dynamometer prototypes enable us to do validation tests for EVs and demonstrate some behavior or property while spending less time and reducing the overall costs.

To expand the knowledge about electric vehicles and better understand the operation and measurement possibilities of a chassis dynamometer, this work aims to develop a small-scale chassis dynamometer prototype for electric vehicle analysis. To meet this general objective, it is necessary to achieve the following specific objectives:

- Analysis of works related to the theme;
- Definition of relevant parameters and their correlates;
- Instrumentation devices suggestions to obtain the parameters defined in the previous item;
- Project requirements listing;
- Conceptual project.

These topics will guide the following sections.

2. STATE OF THE ART

In the automotive industry, chassis dynamometers, also known as roller dynamometers, are commonly used to evaluate vehicles. They enable broader analyses such as durability, fuel consumption, emissions, engine performance, efficiency, emulate standardized cycles and external conditions, as well as components of the vehicles themselves, as emphasized by Bertoti (2018). Also, some advanced these devices are computer-controlled and are capable of simulating driving under real road conditions (Wager et al., 2014) and they are also applied in academic research, once they allow controlling experimental conditions and guarantee the reproducibility of the experiments (Eckert et al., 2017; Bertoti et al., 2019).

Furthermore, the importance of investigating new test platforms for the validation of HEV power systems was emphasized by Mayyas et al. (2017), that made a procedure for the design and validation of hybrid powertrains for performance and energy efficiency using chassis dynamometer. In this way, Chen et al. (2018), Song et al. (2018), Wu et al. (2015), Wager et al. (2014) and Rambaldi et al. (2011) used roller dynamometers to evaluate EVs.

The work developed by Bertoti (2018) describes the dynamometric bench of the Integrated Systems Laboratory (LabSIn) – Unicamp, as seen in Fig. (1). This test bench was modified and improved to allow different and relevant analyses, as seen in Costa (2014), Eckert (2017) and Bertoti (2018). Therefore, it presents some characteristics that should be highlighted:

- The dynamometer has eight rolls of 400 mm diameter each (two contact points per wheel);
- Torque measurement changed from the indirect obtaining with the inertia of the roll to the direct measurement by flange torque wrenches, as emphasized by Costa (2014);
- Rotation measurement was also modified from a 45º resolution incremental inductive encoder to a 6º resolution incremental optical encoder;
- The power transmissions by belts between the axles, which generated many losses, were removed and actuators were assembled only at the frontal axis. (Eckert, 2017). In this way, nowadays the bench can perform front axis experiments and the rear rollers inertia is compensated;
- In addition, reducers were placed between the actuators and the rollers in order to amplify the torque provided by both the brake and the motor (Bertoti et. al, 2019);

This configuration allows us to measure angular speed and torque. Hence, it is possible to calculate other parameters such as linear speed, accelerations, torque and power. The data acquisition was done by the National Instruments modules and LabVIEW programming. LabVIEW programming is widely used in this context software once it allows us to establish an interactive monitoring interface that is easy to understand, both for controlling the parameters of the tests and for monitoring the results, as can be seen in Wager et al. (2014), Rambaldi et al. (2011), Mayyas et al. (2017) and Fajri et. al (2016).

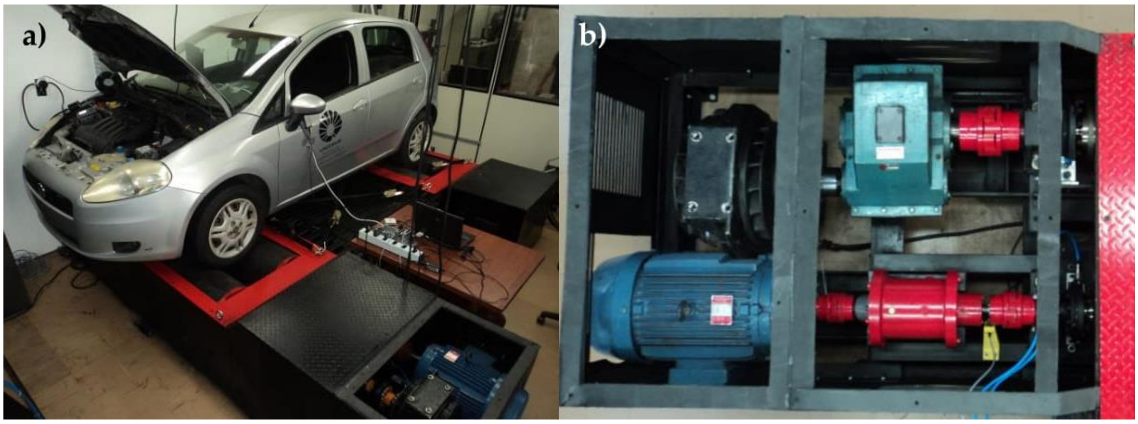


Figure 1. Chassis dynamometer of Integrated Systems Laboratory (LabSIn). Available from: Bertoti (2018).

Lage et al. (2018) is another relevant work. It aims to study the behavior of electric vehicles by building a small-scale prototype of a modular electric vehicle. A few characteristics of the EV prototype should be considered during the development of the small-scale dynamometer. Lage et al. (2018) designed the modular vehicle with independents traction and control on the wheels so that each wheel has its own electric motor and controller. In addition, because it is modularly constructed, the prototype enables the overall dimensions of the vehicle to be changed, both longitudinal and lateral, by varying the spaces between the wheels (truck and wheelbase).

Another inspiring work was done by Fajri et. al (2016), that developed a small-scale hybrid electric vehicle with the most important components of a real vehicle in reduced scale so that the produced prototype has a behavior equivalent to the real one. As can be seen in Fig. (2), this HEV prototype was tested on a small scale chassis dynamometer, also developed by Fajri et. Al (2016). The dynamometer consisted of two stainless steel rolling bars, the inertia of the rollers being calculated on the basis of the weight in the specifications of the vehicle. The rollers were used to emulate the inertia of the vehicle and were mechanically connected to a DC motor with a fixed resistance load to compensate for all the resistive forces applied to the vehicle.

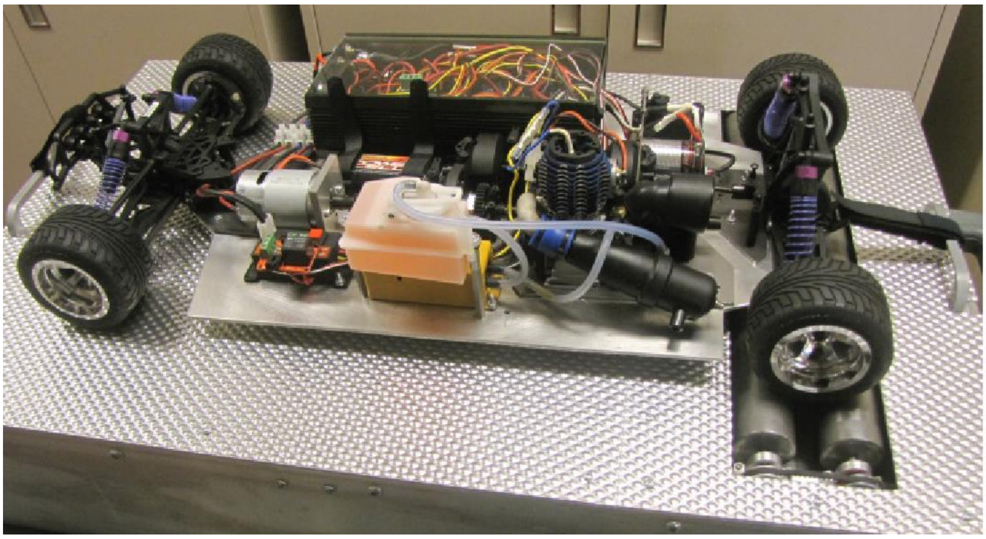


Figure 2. Experimental setup of the small-scale HEV on a chassis dynamometer. Available from: Fajri et al. (2016).

Fajri et. al (2016) provides a sense of the magnitude of the system and its parameters. The gears were capable of reaching speeds of 30,000 rpm and its torque was controlled by a servo motor. A BLDC motor was used as the electric propulsion unit, being able to reach 18,000 rpm with 7.2 V voltage. The generator used was a DC brush motor operating as a generator to deliver a variable DC voltage. A small-scale planetary gearbox was responsible for the distribution of mechanical power between the gear, the generator and the electric motor. A 7.2 V NiMH battery with a capacity of 1200 mAh was used. In this way, it is possible to analyze important characteristics that can be applied to the present work.

3. METHODOLOGY

Among the presented parameters, the most relevant measuring points are the engine torque on each wheel and wheel angular speed. These parameters will be acquired by rotary torque transducer and encoders, respectively. The acquisition of these data over time also allows the achievement of other characteristics such as longitudinal speed, angular and linear accelerations, power and force.

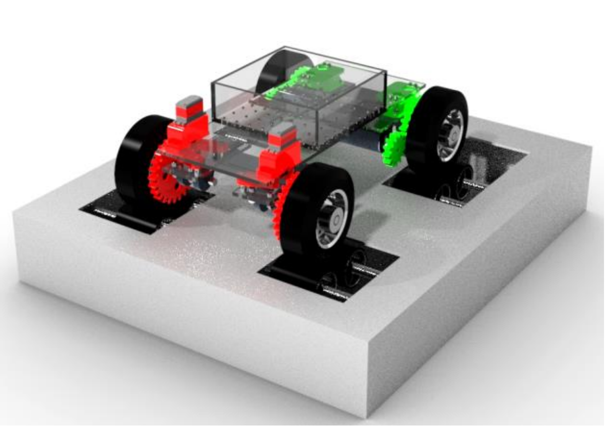
After analyzing the base projects presented and their relevant characteristics, the following project requirements were defined:

- Adjustable distance between the rollers, longitudinal and lateral;
- Two rollers for each wheel (two contact points);
- Components should follow a reduction ratio, relative to real size dynamometers, in their geometry, material and mass properties;
- Motors coupled to the axles to emulate loads of external conditions;
- Torque transducer and encoders assembled with the axes;
- The geometry of the dynamometer must accommodate the sensors and their respective wiring;
- The data acquisition using National Instruments modules and LabVIEW programming;
- Compact geometry that allows assembly and disassembly.

4. RESULTS

Based on the characteristics and relevant requirements of the project, the conceptual project was developed. Fig. 3 shows the 3D modeling of the main components and the modular vehicle that will be test in this test bench. The chassis dynamometer design follows a geometric proportion and the reduction scale is between 4 to 6 times smaller than a real size one, it varies depending on the components and some adjustments it is necessary.

As can be seen in Fig. 3, the design has a simple geometry. The outer case protects the internal components and allows the rollers to contact the outside to support a vehicle prototype. The openings in the upper part allow the position of the rollers to be changed so that the test bench is able to evaluate vehicles with different tracks and wheelbases. Details about this adjustment system are given in subsection 4.2, this adjustment is differential compared to existing test bench. It is also interesting to note that this bench has two points of contact having some advantages and disadvantages, one of them being the increase of the rolling resistance, however it generates a better stability in the tests.



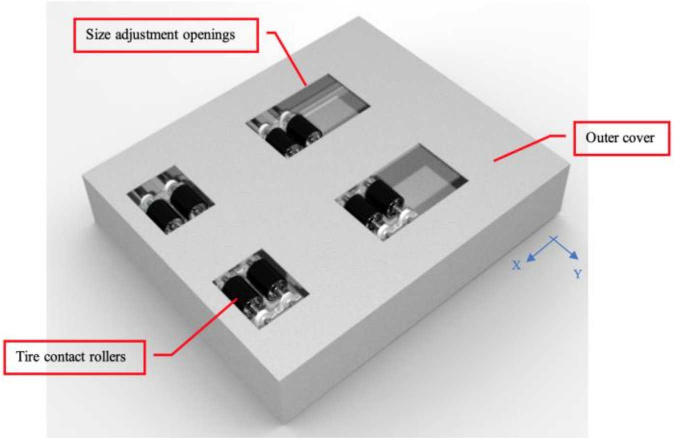


Figure 3. External view of the 3D model.

4.1 Equivalent inertia

A chassis dynamometer allows the analysis of the vehicle performance and, in this way, it is necessary to understand the movement resistances involved. Therefore, a key parameter to ensure an accurate emulation of the vehicle movement resistances forces is the rotational inertia of the dynamometer bench rollers. In the case of a 4x4 chassis dynamometer, the 8 rollers inertia I_{rol} [kgm^2] must represent the vehicle longitudinal displacement.

The required vehicle equivalent inertia I_{req} [kgm^2] is defined considering the kinetic energy of the vehicle longitudinal displacement should be equal to the energy of the rotation of the rollers as presented in Eq. (1).

$$\frac{1}{2}m_{eq}V^2 = \frac{1}{2}I_{req}\omega_c^2 \tag{1}$$

Where V [m/s] represents the vehicle speed, ω_c [rad/s] is the dynamometer rollers angular speed. In the presented study, the developing bench is designed to small-scale vehicles, (usually ranging from 16% to 25% of a real vehicle) and therefore, the tested vehicle mass m_{eq} [kg] is also defined according to the scale of the emulated vehicle.

If the tires longitudinal slipping, (usually below 2% in hard ground contact (Nicolazzi et al. 2001) is neglected, the tangential speed of the vehicle tire in the contact with the rollers can be considered the same. Therefore, the ω_c is defined by Eq. (2) according to the roller's radius r_c [m]. Moreover, Eq. (1) and Eq. (2) can be assembled and simplified to define the bench required inertia I_{req} [kgm^2] as shown in Eq. (3).

$$\omega_c = \frac{V}{r_c} \tag{2}$$

$$m_{eq}V^2 = I_0\left(\frac{V}{r_c}\right)^2 \therefore I_{req} = m_{eq}r_c^2 \tag{3}$$

However, the resulting I_{req} value may not be equal to the existing inertia of the bench 8 rollers (I_{rol}). The difference among the required and exiting inertias I_{comp} [kgm^2] is defined by Eq. (4) and it will be compensated by adding discs in the rollers axis, as can be seen in Fig. 4.

$$I_{comp} = I_{req} - I_{rol} \tag{4}$$

These compensated discs are masses with known values which, in the case of small-scale bench as proposed in this paper, can be applied and are easily assembled and disassembled. However in the case of full size dynamometer, this inertia correction should be avoided by sizing suitable rollers for each vehicle.

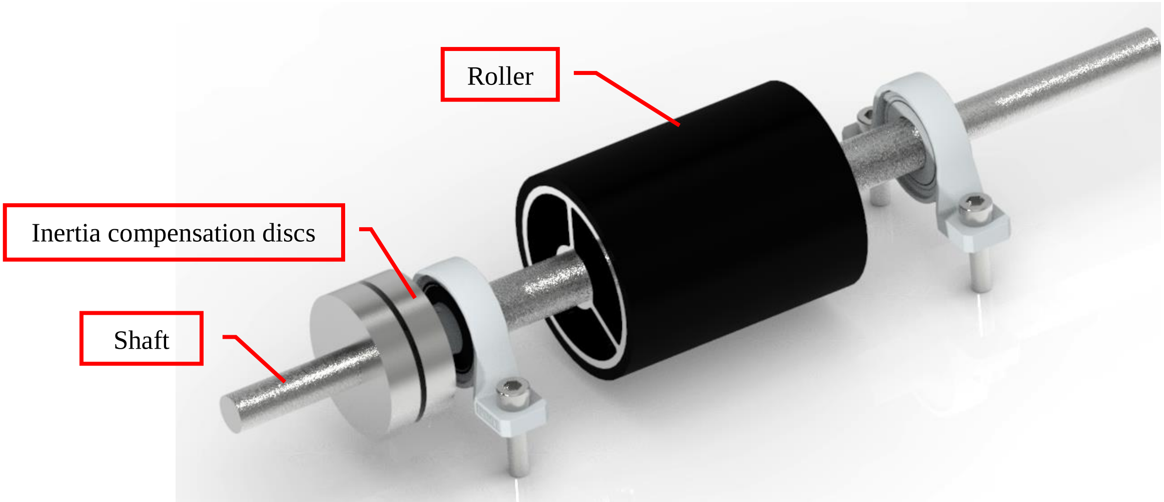


Figure 4. Detail view of components: inertia compensation discs, roller, and shaft.

4.2 Size adjustment system

As relevant characteristics, it is worth to emphasize the size adjustment system, which allows us to change the distance between the rollers, lateral (axis Y) and longitudinal (axis X). Therefore, it makes the test bench able to evaluate a range of vehicle prototypes of different sizes, as can be seen in Fig. 5.

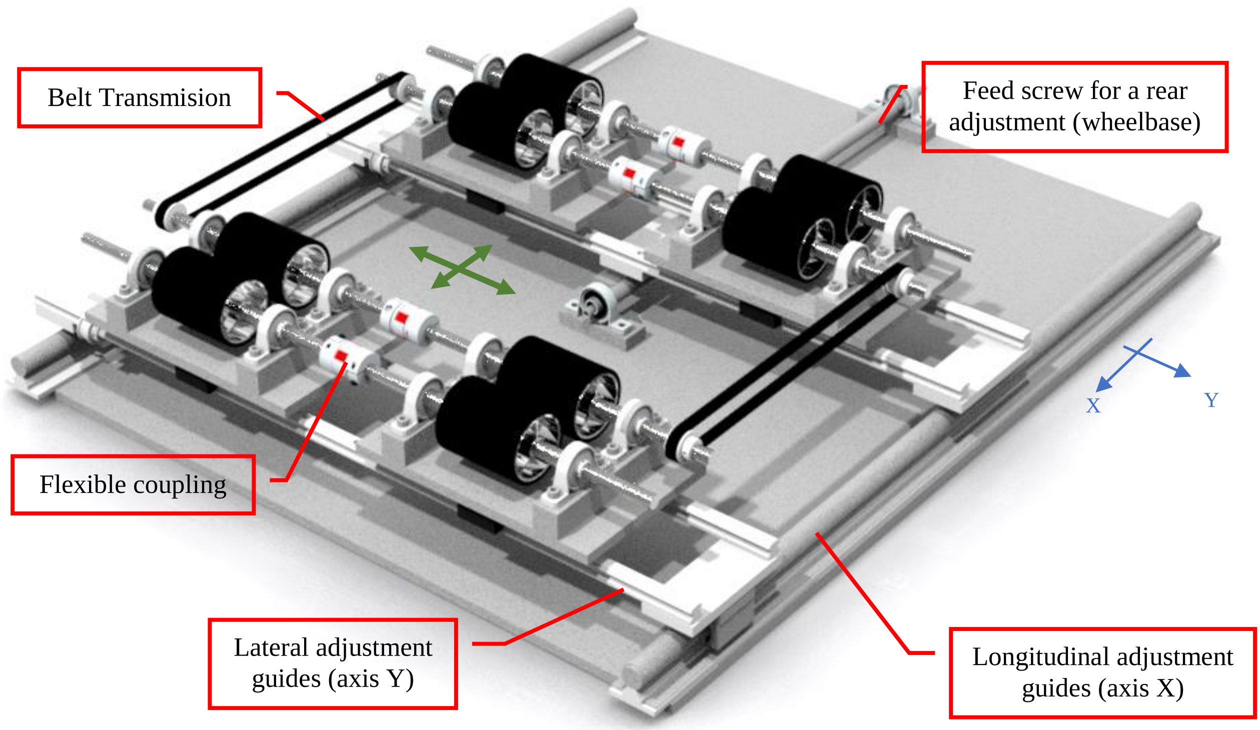


Figure 5. Size adjustment system details.

As can be seen in Fig. 5, the lateral adjustment guides allow the rollers of the bench to move along the axis Y for both sides. Thereby, the track of the bench can change and, hence, the vehicle track width on the test also can change. This way, the platform is able to test vehicles with track values between 330 to 450 mm.

Similar behavior happens for the X-axis. The longitudinal adjustment guides enable the rollers of the bench to move in axis X, as shown in Fig. 5. In this case, only the rear rollers change along the X-axis and the movement is done by a feed screw and linear guides, one on each side of the platform. This way, the tested vehicle wheelbase can be adjusted among 388 and 538 mm.

4.3 Transmission and power

When the vehicle prototype into operation is on the workbench and rotates its wheels, it also moves the rollers it makes contact with. In this way, power is transmitted from the vehicle to the rollers and hence to their axes of rotation and all that is connected to them. Motors and brakes will be connected to the ends of the axes to simulate bigger or lesser resistance to movement. Compared to the actual use of a vehicle, these resistances would be equivalent, for example, to driving downhill and uphill.

A flexible coupling is used to connect two shafts together at their ends to transmit power on the same axis, as pointed in Fig. (5). Even using a flexible coupling to connect the roller, the assembly should be aligned to avoid an excessive force on the motor, sensor or other equipment.

Also, another important point is the power transmission between the rear and the front axis. In some tests, depending on the vehicle configuration, it is necessary that the rear and front axles should be independent, however, in other cases, it is necessary to connect them. Therefore, this bench will transmit power between them using belts and pulleys, as can be seen in Fig. (5). The belt transmission is 98% efficient, produces little noise and absorbs more torsional vibration of the system than gear transmissions (Budynas and Nisbett, 2011).

4.4 Instrumentation

To measure the speed of the rollers a rotary encoder will be used. The encoder is read by opaque and transparent radial windows that are illuminated by an infrared light source. A receiver converts the light signal into electrical pulses, so when light passes through the transparent window the encoder drops the voltage signal. By varying the time of each voltage drop it is possible to determine the angular velocity of the shaft.

Another important point is the torque measurement. For this, two main approaches are possible. The first one is the usage of a torque sensor, in which the sensor shaft is connected to the axis of rotation, the bench rollers in this case, for power transmission. Sensor output cables are connected to the acquisition system. The other approach is the use of strain gages, transducers that varies their electric resistance according to the deformation on the structure. The variation of electric resistance in a Wheatstone bridge circuit generates a voltage output signal proportional to the deformation and, hence, to the force and torque applied. In this way, torque information can also be obtained. The challenge of this approach is the wireless transmission of the output signal since the strain gages would be attached to moving axes, not allowing cabling to pass through.

5. CONCLUSION

It can be concluded that the general objective of this work has been reached, presenting a small-scale chassis dynamometer design for vehicle prototype analysis. In this way, the following is an assessment of the specific objectives initially defined:

- Relevant works for the development of the project were analyzed;
- These analyses allowed us to define the relevant parameters and their correlated;
- The relevant project characteristics and requirements were listed;
- Instrumentation devices were suggested;
- Finally, the 3D modeling of the components was showed and the designed components followed a reduction ratio in their geometry and mass properties;

Therefore, this work resulted in a small-scale chassis dynamometer conceptual design, a bench able to test a range of prototypes and which encourages the development of this kind of platforms.

In future works, this small-scale dynamometer will be made and the modular vehicle will be test to study dynamic behavior.

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