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EXPERIMENTAL RESEARCH REGARDING THE STABILITY OF THREE WHEELS SMALL ELECTRIC VEHICLES

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Electrical tricycles are becoming a better alternative to the heavy traffic in all big cities. There are already several designs of electrical tricycles on the market, but all of them are using rigid articulation of the main frame. The product proposed by this paper is built using a rubber articulation whose primary purpose is to act both as a revolute joint and as a suspension. By using rubber-based articulations, we can provide a better dynamic behavior of the electric vehicle so that we could improve overall performances on bumpy roads.

Keywords: tricycle, foldable vehicle, electric vehicle.

1. Introduction

Nowadays, it can be observed a significant increase in the electrical bike/ tricycle industry. Important factors that have favored this development are related to climate changes determining policy makers to encourage that various facilities are made available worldwide to those who wish to become involved in the development of this industry.

The most used alternatives for classic cars are still classic motorcycles, motor scooters, and bicycles. Nevertheless, in this category, to travel for short distances, there are becoming more and more present also electric scooters or different types of tricycles.

Thus, the designer’s interest was directed to the creation of a vehicle that would combine the main advantages offered by both the car and the motorcycle, and who would offer a higher degree of comfort when used and would be easy to handle. One such vehicle could be a tricycle as it combines advantages from both cars and motorcycles, but it is lighter and easier to carry.

2. Theoretical aspects

The tricycle with a classic design, without a tilt system, can behave like a 4-wheel vehicle. This is because the center of gravity is placed as close as possible to the common axis of the two side wheels. For such a system to work, the ratio between the width and the height of the tricycle must be considered as it

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is directly proportional to the resistance that can be generated when overturning.

As Robert Riley explains in his paper "Three wheel cars" [1], a simple way to model the safety margin of conventional tricycles in relation to overturning is to build a cone using the height of the center of gravity and maximum lateral forces, which are determined by the coefficient of friction between the tires and the pavement. If the resulting maximum turning force is projected towards the floor, the base of the cone is formed, considering that a force equivalent to 1G through the vehicle will result in an angle of 45º toward the ground plane. If the base of the cone is outside the effective area of the tricycle, it will turn before skidding; on the contrary, if the circle falls within the active area, the vehicle will skid rather than tip over. In Fig. 1 one can see the schematic analysis mentioned above for tricycles with one front wheel and two rear wheels (1F2R), and for conventional tricycles with two front wheels and one rear wheel (2F1R).

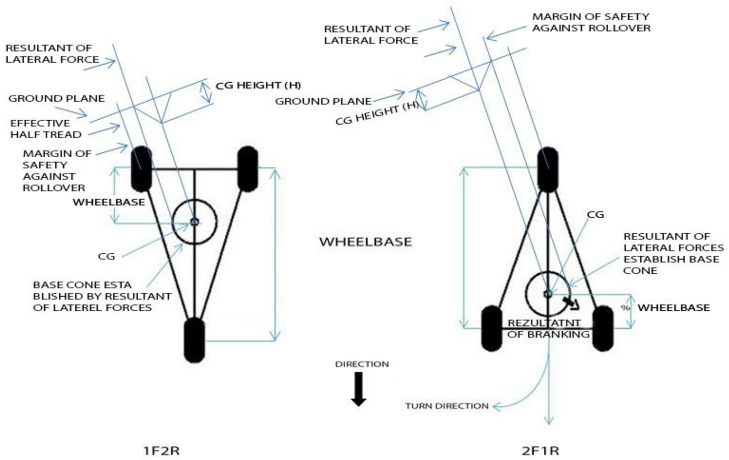


Fig. 1. Evaluating the safety factor for vehicle overturning for the two main wheels configuration (1F2R and 2F1B) [1]

The two models that were studied in this paper are the one with one wheel in front and two wheels on the rear axle (1F2R) and the one with two wheels in front and one rear wheel (2F1R).

The major notable difference is the weight center. While on the 1F2R model it is placed closer to the back axle, for the second model, the experimental research regarding the stability of 3 wheels small electric vehicles weight center, is placed to the front of the vehicle.

This aspect significantly influences the behavior of the tricycle on curves. The 1F2R design tends to oversteer, while the second model, the one with two front wheels, tends to understeer. For the inexperienced user, the best model is the one with two fronted wheels as the understeer is preferred.

Another important aspect regarding vehicle stability is behaviors during acceleration and braking stages. When braking on curves, the 1F2R model tends to unbalance as the 2F1R model tends to unbalance on high accelerations. As usually, the braking force is larger than the acceleration, one may say that the best model is the one with fronted two wheels.

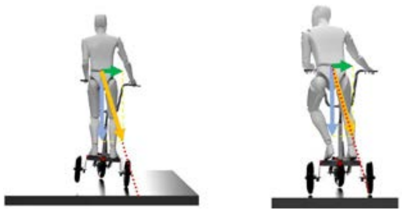
a) oversteer b) understeer

Fig. 2. Oversteering (a) and understeering (b) of a vehicle [2]

Unlike the motorcycles (Fig 3) the vehicle stability on curves is limited by the wheelbase (Fig 4, a, b). On steering motorcycle, the tilt of the bike compensates the centrifugal force.

Fig. 3. Forces on steering motorcycle [3]
(Green – centrifugal force, blue – gravity force, yellow – resulting force)

Rigid tricycles behave in curves almost like cars so, in order to compensate for the centrifugal force, the driver must change position (Fig 4, b) otherwise, the vehicle could lose stability.



a) b)

Fig. 4. Steering forces on a tricycle - a, b without tilt wheels.

In order to overcome this limitation, three wheels vehicles could be equipped with a tilt mechanism. The tilt can be permitted on one wheel (Fig. 5), two wheels or on all wheels.

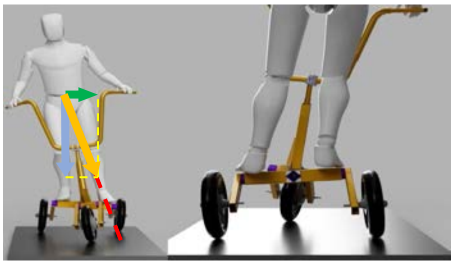


Fig.5. Steering forces on a tricycle -; with tilt wheels
(Green – centrifugal force, blue – gravity force, yellow – resulting force)

Another obstacle for engineers and designers alike was to adapt different propulsion equipment to the tilt mechanism of the tricycle. This drawback was overcome by wheel integrated electrical motors.

In the case of the 1F2R tricycle model, the motor is positioned in the front wheel, which is also responsible for steering. In the case of the 2F1R tricycle model the motor is positioned in the rear wheel, while the front wheels are responsible for the steering, the latter model having the possibility to use another hybrid system of engaging, which is both electric via the motor or through pedaling.

3. Tricycles tilt mechanism

The tricycle can have a free tilt system like an ordinary motorcycle or tilt assisted system, which is responsible for tilting the vehicle (Fig.6).

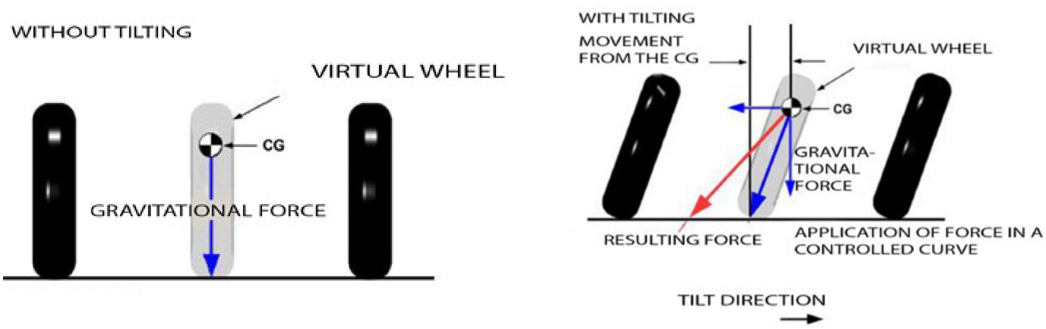


Fig. 6. Steering forces on a tricycle equipped with a tilt mechanism [4]

Forced tilt systems work with hydraulic or electromechanical actuators, which are operated under the signals of an electronic control unit (ECU). Normally, the ECU processes signals from sensors that monitor lateral acceleration, vehicle tilt, steering angle.

Another advantage of the active control system is that the user does not have to balance the vehicle as for the motorcycle. With the active control system, the vehicle is driven just like an ordinary vehicle because the system handles the rest of the operations. On the other hand, the free tilting system is much simpler, as in the case of a motorcycle, the user determines through his interaction with the vehicle and the conditions of the terrain, which is the most suitable angle to take a curve. An analogy could be made by saying that, for this type of systems, the sensors that monitor lateral acceleration, vehicle inclination and steering angle corresponding to the pilot senses, while the actuators responsible for providing the vehicle with the optimum inclination correspond to the user's power and body weight.

Determining which tilt system is better depends on the user's preference. For an easy and comfortable transport vehicle, an assisted tilting system is very likely to be chosen. On the other hand, for a sportier driving experience, in which there is a more direct interaction with the vehicle and the road, the unassisted tilt system is more appropriate.

4. Suspension system

When steering a vehicle with tilted wheels, the force applied to each wheel will increase as the tilt angle will increase. The suspension system purpose is to absorb the different variation on the load force. Another main task of the suspension system is to absorb shocks from different small road obstacle or bumpers. In a vehicle, the shock absorbers reduce the effect of travelling on rough terrain, which results in improved ride quality and vehicle handling.

A damper is a mechanical or hydraulic device designed to absorb shocks. It does this by transforming the kinetic energy of the shock into another form of energy (usually heat) which is then dissipated.

In most shock absorbers, the energy is converted to heat inside the viscous fluid. In hydraulic cylinders, the hydraulic fluid is heated, while in hot air cylinders, hot air is usually exhausted into the atmosphere. In other types of shock absorbers, such as electromagnetic types, the dissipated energy can be stored and used later. On rubber-based shock absorbers, the kinetic energy is transformed in elastic energy; thus, this kind of dampers could also be used as a suspension without any other elastic elements like helicoidally or torsional springs.

On commercial vehicles, usually, hydraulic dampers are used in most cases, but there are also examples of rubber-based dampers.

Pneumatic and hydraulic shock absorbers are used together with springs. A car shock absorber contains control valves and spring control parts for controlling the flow of oil through an internal piston. In the case of portable vehicles, we cannot afford to include hydraulic shock absorbers mainly because this will increase the price and overall dimensions of the final design.

Nowadays there are several elastic, rubber-based, damping systems, designed and used by several companies, having different shapes and solutions depending on the tasks that they must bear and fulfil. When designing a compact tricycle, the suspension system must be as compact as possible. This is the reason why two solutions are widely spread: rubber flexible system working in shear (Fig.7.) and four rubber flexible systems working in compression (Fig.8.). The main advantage of those suspension/damping systems is that they can be integrated into the vehicle chassis structure.

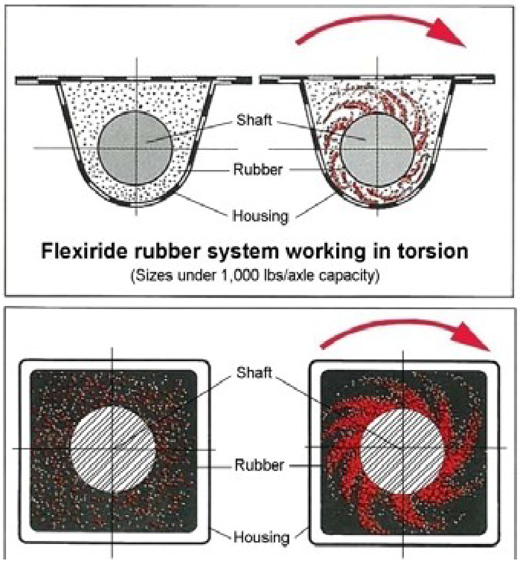


Fig.7. Rubber system working in shear [5]

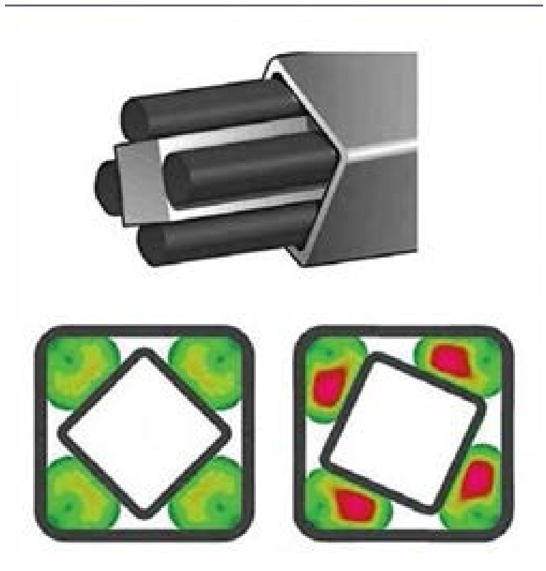


Fig 8 Compression based rubber system [6]

5. Tricycle CAD concept, static and dynamic analysis

We chose to develop a frame with one front wheel and two back wheels. For our compact tricycle design, we added 4 ROSTA rubber articulations, one for each wheel and another one as a tilt mechanism for the front wheel. In Fig. 8 is presented the Rosta articulation and in figure 9 the implementation of the Rosta articulation on the tricycle frame concept [6].

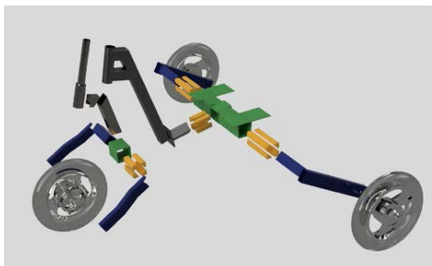


Fig. 9. The final CAD concept of the product

For the second model (Fig. 10), a physical prototype concept was built and tested on real road conditions. For further development of the tricycle frame, a research on the distribution of weight on tricycle wheels was necessary, to be able to recreate real usage scenarios for structural optimization.

To determine the loading values of the tricycle under the weight of the operating user, there were used scenarios, of which a scenario with the frame without load taken as a reference, and three scenarios with the frame under the weight of the user, on braking, on the left turn and turn right. For the measurements, three identical, calibrated weight scales positioned under each wheel of the tricycle were used.

From the distribution of the own weight of the frame together with the adjacent components with a value of 313.81 N in total it resulted that on the front axle are distributed 166.71 N and on the rear axle were 73.54 N on each arm.

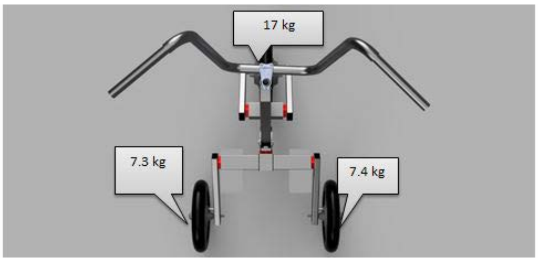


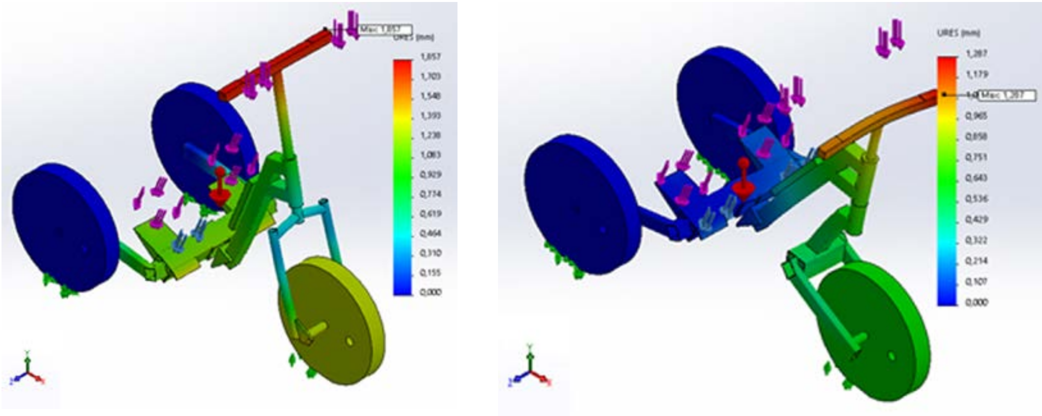
Fig. 10 – The weight distribution of the frame without the user load

In the usage scenario, which takes into account a user that has a mass of 106 Kg and the weight of the tricycle, the distribution of the total weight at rest was as follows: 535.44 N on the front axle and 408.94 N on the rear axle on each arm. In the braking scenario, the total weight distribution was front axle 713.92 N and rear axle 319.7 N on each arm. In the use scenario in which the tricycle was on the turn the distribution of the weight was as follows: the front axle 470.72 N and on the rear axle on the arm inside the turn 698.23 N and on the arm outside the turn 184.36 N.

The results contributed to the optimization of the tricycle framework regarding finite element analysis by providing the parameters necessary for the mechanical loading of the tricycle and its constraint during static tests. The studies were carried out in the Solid Works [7] modelling and simulation program using the static simulation module "static stress".

For the simulation we considered several aspects that are important for the final product. For starters, the rear wheels were locked at the level of the ground surface, and the front wheel was left free sliding over the entire surface, the variant was also tried with all the wheels locked, the result being static indeterminate. The choice of locking the rear wheels and leaving the front axle free was chosen, this constraint having a negative effect on the behavior of the front damping system.

The mechanical load was distributed at the handlebar level and at the support point level of the frame legs with a value of 1040 N. The stress state of the frame and the frontal damping system were monitored in the three situations in order to identify the critical areas in which the forces exceed the value admitted to the resistance of the material from which the tricycle structure is made.



a) Maximum deformation 1,857 mm b) Maximum deformation 1,287 mm

Fig. 11 Analysis of maximum deformations

Taking into account the values obtained from the above analysis, the second variant of the frame was selected for further testing and development.

The frame analysis steps are as follows:

The tricycle structure was fixed on the "x-y" plane by the rear wheels with the "roller/slider" type constraint. The chosen frame and fork material in this study is carbon steel and the load applied to selected key surfaces of the frames (where the user weight rests on the tricycle) with a force of 1040 N. For this experiment we used a static analysis. Following the analyzes performed, the maximum deformations of the frame can be observed in Fig.11. In first version (Fig.11 a) using a classic fork-type geometry, after applying a force of 1040 N the frame had a maximum deformation of 1.85 mm, the area with maximum deformation being at the top of the handle bar. By modifying the front geometry of the frame of the second version, the frame deformation was reduced to 1.27 mm. The use of a viscous-elastic damping system brings advantages over the stability of the vehicle and offers better resistance to the frame, eliminating some of the stress states that appear in the classic fork structure. The analysis shows that the version 2 (Fig. 11b) of the tricycle presents the optimal frame design for further development, thus the next step is to create a real-life experiment using strain gauges mounted in essential areas of the structure.

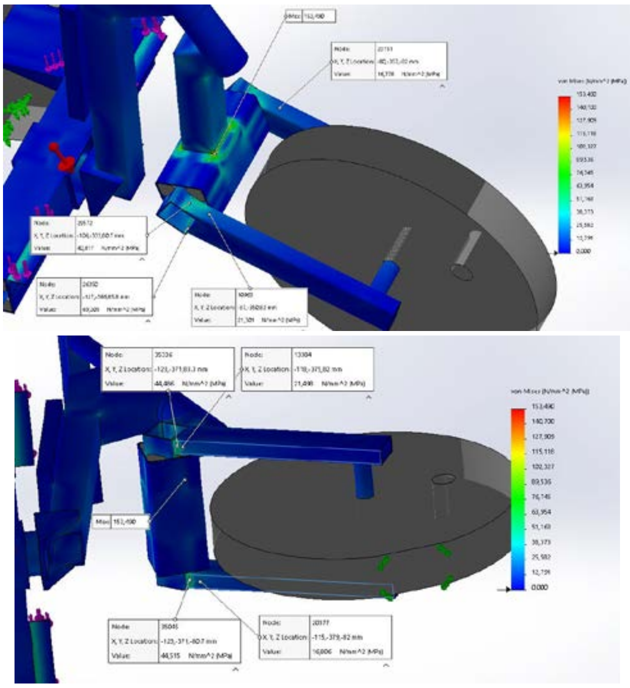


Fig. 12 – The areas where the maximum fork tension develops – Von Mises for version 2

„ In order to establish the critical points to be measured in the structure, the maximum strain areas in the frame were chosen to determine the placement of the strain gauges (Fig. 12).

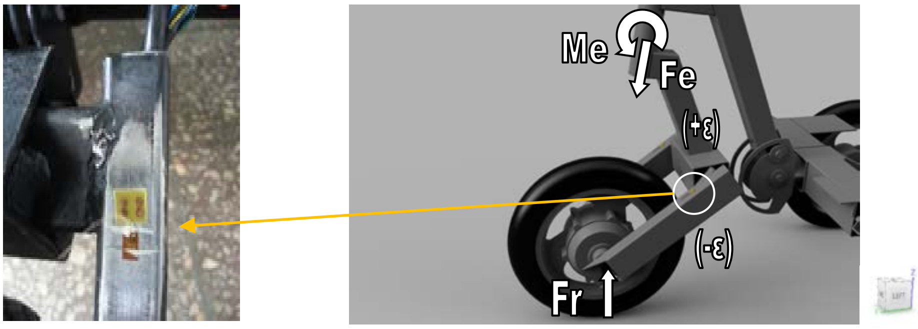


Fig. 13 - Bonding of tensometric transducers installed on the fork arms

Strain gauges model BF120-3AA were used in a type II half-bridge configuration like in Fig. 13 and Fig. 14 [8]. In this set-up, only bending efforts are measured. By using this set-up, both tensile strain (+ε) and compressive strain (-ε) are measured.

From the half bridge equation strain can be computed from excitation voltage (V_0) and strain gauge factor (GF)

$$\frac{V_0}{V_{EX}} = -\frac{GF \cdot \varepsilon}{2}$$

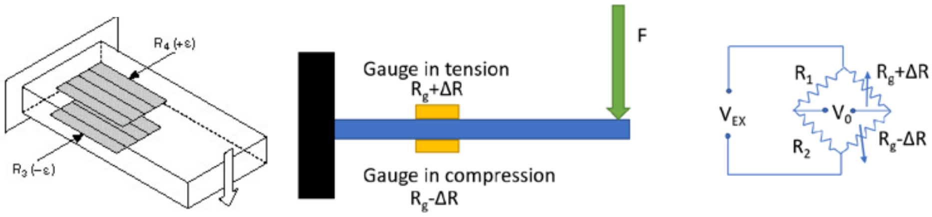


Fig. 14 – Half bridge type II configuration [8]

The strain gauge transducers [9] [10] were mounted on the rear axle arms and on the fork arms at 60 mm (Fig. 13) from the articulated end of the arm.

All strain measurements were performed using a virtual instrument – Lab View (Fig15). National instruments predefined virtual instrument called “Strain – Continuous input multichannel”. Based on the bridge configuration and strain properties, from measured voltage (mV), bending strain is automatically computed. The input parameters of the virtual instrument are strain gauge’s properties like nominal resistance, gauge factor; measuring set up (half bridge type II). The output of this predefined virtual instruments is a sequence (time series) of strain values. To compensate for the wire internal resistance an initial bridge voltage is measured and used to balance the Wheatstone bridge.

Using this instrument stress was computed from acquired strain data and materials young’s modulus. Acquired data was also logged and compared with data from FEM simulation to correctly compare and identify the best solution. By using the National Instruments (NI 9191) Wi-Fi acquisition board and the NI 9215 module acquisition was performed wireless in open space.

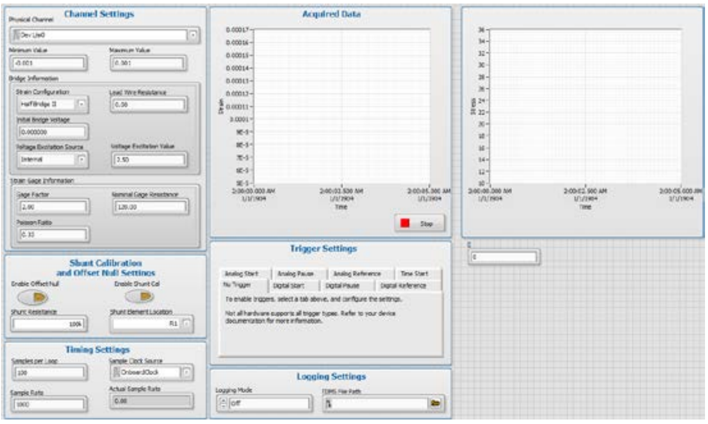


Fig. 15 Lab View virtual instrument

The fig.16 shows the loading conditions of the tricycle when the user climbs and leaves, the loading conditions of the tricycle when crossing an obstacle with the front axle and its balancing / returning state observing the period of oscillations.

Fig. 16. Dynamic analysis, measurements on the real prototype

Relevant results in scientific literature are focused on mechanical simulations, as well as on structures that have better energy absorption. These systems ensure a good efficiency of shocks but can generate, an increase in user effort [11].

In Fig. 16 above shows the dynamic behavior of the tricycle in different scenarios of use overcoming the obstacle and turning 360 degrees under a constant weight of the user [12].

The tension state on the right and left rear axle in relation to the forward direction is highlighted in the following graphs by:

• red tension state measured by strain gauges mounted on the left rear arm

• dark blue / white tension state measured by strain gauges mounted on the right rear arm

• green color tension state measured by strain gauges mounted on the left arm of the front fork

• light blue color the tension state measured by the strain gauges mounted on the right arm of the front fork.

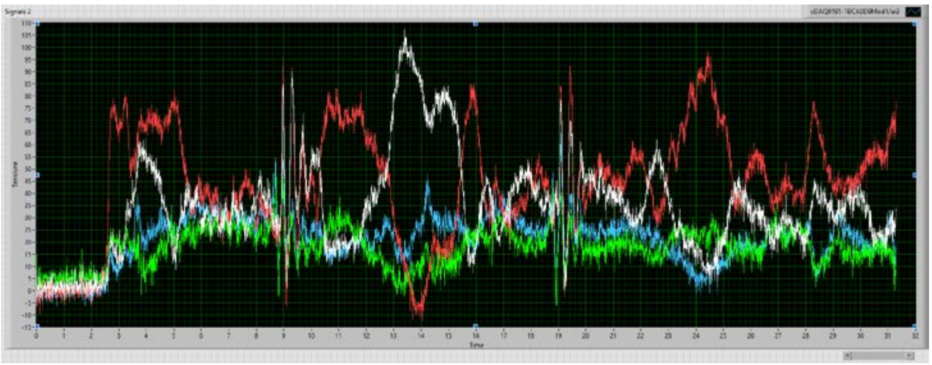


Fig. 17. Measurements obtained from the strain gauges during the dynamic test

6. Conclusions

The aim of this research was to develop an electrically foldable tricycle easy to use yet robust, able to offer a comfortable driving experience on every road type. The main contributions consist in designing the tricycle structure together with the folding mechanism, developing a suspension system specifically for the frame using the elastic damping elements and measuring strain values in several key locations on tricycle frame using strain gauges. In order to achieve those, a physical prototype was built and improved based on measurements performed during this research.

The main outcome is that bike stability could be greatly increased by using a ROSTA type suspension/damping as a tilt mechanism. As expected, after testing the vehicle on the road and gathering data from the analysis, we came to the conclusion that the rubber suspension makes this vehicle more sporty and suitable for all types of terrain, because it has helped to attenuate the vibrations that in its absence would have been taken over by the user. As a conclusion of this research using real and virtual prototypes as well, the 1F2R solution emerged as the best one with the best results in terms of stability from the three wheels small electric vehicles analyzed.

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