STUDY OF THE LATERAL DEVIATION OF ELECTRIC BICYCLE AS FUNCTION OF THE TOTAL MASS AND THE BATTERY POSITION

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Abstract: *The paper examines the dynamic behavior of an electric bicycle depending on the total mass of the bicycle, the cyclist and the battery on the one hand and on the other - on the place of the battery. The experiment demonstrates that in its movement at a constant speed the electric bicycle behaves as inverted pendulum.*

Keywords: electric bicycle, lateral deviation, planned experiment, weight, battery position

1. Introduction

With more than $100*10^6$ bicycles produced every year for the period of 2005-2014, and constantly increasing share of the electric bikes – 33% of all produced bikes for 2014, electric bicycles are taking a huge part of the market. In other words, these not that modern vehicles (the first patent is from 1898 by O.Bolton [9]), that have been neglected in the past because of their high weight and short range are currently seeing their renaissance. It started in 1990 by using lighter and more powerful batteries and drastically increased by the introduction of improved Lithium-Ion batteries in 2002.

The electric bicycles are ecological vehicles and with guaranteed speed limit of 25 km/h are fitting in the category of traditional bicycles which allows them to be used on velo-paths and in parks. They are also free of tax compared to other motor vehicles. They require minimal parking space and at the same time allow the rider to reach long ranges with less muscle power, especially while climbing steep hills. Regardless of their still high price (1500÷8000 €) electric bicycles are constantly increasing their market share. In addition some Bulgarian manufacturers as DRAG [6], CROSS [5] and ZECOTEK [7] are introducing their own electric models with satisfactory sales.

Some of the biggest automotive brands as Mercedes, BMW, Smart, Opel and Audi are also introducing their own electric bikes as in the case of Smart we are seeing a second generation of their model. In addition there are other brands that have focused only in the production of electric bicycles like Gocycle [8]. In all models serious attention has been paid to the design of the vehicle as a major factor that affects the sales of the product. In addition some of the ads are presenting the bicycle as integral part of a car of the same brand. In these cases the topic about the correct placement of the battery and the impact of the total weight of the bicycle are often neglected. A serious omission compared to the huge number of theoretical studies on the dynamics of standard bicycles [13] etc. In the scientific fields there is a long dispute about the justification of the stability of these quite popular vehicles which are the objects of different studies [12] and design [10]. The main dispute is whether the inverted pendulum effect or the gyroscopic one is determinative for the stability of the vehicle in motion. As a result it becomes clear that in motion with constant and relatively high speed the weight should be placed as high as possible analogously to the "construction" of some high-speed animals as horses, deer and antelopes. At the same time it is well known that during starting and stopping or low speed movement it is better if the mass center is located lower. In other words it is required to find an optimal compromise solution of this task.

In two previous articles by the author of the current one was made a multifactor comparison of the constructions of electric bicycles produced by leading manufacturers and it was also empirically proved that the position of the mass center of the bicycle is a function of the battery position.

The purpose of the current article is to present the result of an experiment with existing electric bicycle with the lateral deviation as a parameter and the total sum of the bicycle, battery and rider as one input factor and the height of the battery position as another.

2. Essentials of the study

To achieve the aim of the study we held a complete factor experiment [1], [2] of type "FPE3^2", with matrix presented in table 1 with input factors and parameters:

- X_1 и X_2 – the code values of the first – total weight of the rider + electric bicycle + battery G, kg) and second input factor – the height of battery position - *H* cm placed on the frame on the axis defined by the head tube and the pedals;
- Y_{1E} , Y_{2E} and Y_{3E} are the values for the lateral deviation measured during the experiment – vibration displacement during crossing an obstacle with constant height h = 4 cm, with movement speed of 15 km/h, and total mass, respectively G_1 = 125 kg, G_2 = 100 kg and G_3 = 75 kg, and height of the battery position respectively H_1=70 cm, H_2=65 cm and H_3=60 cm.

The experiment was held on a horizontal alley with flat surface. The height of the battery position was controlled by meter and for zero base was used the surface of the terrain. The battery was fastened in the required position with plastic brackets.

The riders selected for this experiment, including the author of this article, were with linearly increasing weight in order to achieve the corresponding linear raise of the input factor – total mass of the rider, the electric bicycle and the battery. The total weight of the bicycle and the battery varies of 25 to 50% of the weight of the rider. The riders maintained a constant speed measured by a controller of the Shimano brand mounted on the handlebar. During the experiment the movement was accomplished by using only muscle power and not electric assistance in order to achieve better safety for the participants in the experiment and to allow them to concentrate more fully on their side task – manual control of the vibration meter and the movement speed. The experiments were conducted multiple times in order to avoid random mistakes related to the maintenance of constant speed, the required time for activating the vibration meter, the need of proper balance during the bicycle movement etc.

On the asphalt terrain an artificial obstacle was mounted – hard wooden block with length of 1 meter and calibrated square cross-section. In order to reduce the hit of the impact as an alternative a PVC pipes with proper diameter were used. The results from the experiment showed that there is no significant difference between values of the lateral movement as a function of the obstacle cross-section. The wooden blocks were properly mounted to the terrain with steel nails.

The parameter (lateral vibrational displacement) examined as a characteristic of the dynamic behavior of the electric bicycle was controlled and recorded with portable vibration meter IL-V 12000. The vibration meter was mounted on the handlebar with securing strap close to the right hand of the rider in order to give maximum convenience of use to the rider – using the thumbnail for turning it on and off and resetting the value during movement.

The portable vibration meter is realized with piezo sensor, amplifier, linearizing block and LCD display. It has its autonomous power source thanks to two batteries by 1.5V each (SR44). The dimensions of the vibration meter are commensurate to a pen and its weight is 44 grams which means that it could not affect the values of the studied parameter.

On fig.1 is presented the electric bicycle used for this experiment which is produced by Drag LTD – Sofia.

Fig.1. *The electric bicycle used in this experiment, produced by DRAG LTD [6]*

The aim is to develop a mathematical-stochastic model of second order of the following type:

$$Y= b_0 + b_1 . X_1 + b_2 . X_2 + b_{12} . X_1 . X_2 + b_{11} . X_1^2 + b_{22} . X_2^2 ,$$

where the unknown parameters are calculated based on the following formulas [2]:

$$b_0 = \frac{5}{9}\sum_{j=1}^{9} x_{0j}.\bar{y}_j - \frac{1}{3}\sum_{i=1}^{2}\sum_{j=1}^{9} x_{ij}^{\,2}.\bar{y}_j$$

$$b_i = \frac{1}{6}.\sum_{j=1}^{9} x_j.\bar{y}_j \qquad b_{ik} = \frac{1}{4}.\sum_{i=1}^{2}.\sum_{j=1}^{9} x_{ij}.x_{kj}.\bar{y}_j$$

$$b_{ii} = \frac{1}{2}.\sum_{i=1}^{2}\sum_{j=1}^{9} x_{ij}^{\,2}.\bar{y}_j - \frac{1}{3}\sum_{j=1}^{9}\bar{y}_j$$

Table 1

j / i	X_1 / G_j, kg	X_2 / H_j, cm	Y_{jE}	$Y_{cp.} = \frac{1}{3}\sum_j^3 Y_j$	Y_M
1	+1 / 125	+1 / 70	16,2; 7,4 ; 10,8	11,47	10,15
2	0 / 100	+1 / 70	10,0; 11,7; 14,6	12,10	13,87
3	-1 / 75	+1 / 70	22,9; 21,3; 18,9	21,03	23,09
4	+1 / 125	0 / 65	12,9; 17,0; 19,5	16,47	14,51
5	0 / 100	0 / 65	11,1; 10,7; 13,3	11,70	17,36
6	-1 / 75	0 / 65	24,7; 23,9; 26,4	25,00	25,73
7	+1 / 125	-1 / 60	8,2; 5,6; 13,7	9,17	9,94
8	0 / 100	-1 / 60	24,8; 17,8; 28,8	23,8	21,94
9	-1 / 75	-1 / 60	13,1; 12,7; 20,1	15,30	19,45

With algorithmic code and the assistance of software tool - MATLAB [11], the parameters of the model are calculated, their impact is verified and is made a check of the model adequacy. The model in a coded form is the following:

$$Y=17,3633-4,0367.X_1-0,6117.X_2-0,8587.X_1.X_2+0,5400.X_1^2-2,2450.X_2^2 .$$

Based on the parameter values of this model and signs of coefficients we can make the following conclusions:

- the value of free coefficient b_0=17,3633 is higher compared to the rest of the parameters which means that there are additional factors that have not been taken into attention with this model;
- the signs of the liner factors (b_1 and b_2) and in front of the pseudo-linear one ($b_{1,2}$) are negative which leads to the conclusion that with the increase of the input values we are seeing reduce of the value of the parameter – the lateral deviation;
- the coefficient $|b_1|$ = 4,0367 is bigger than $|b_2|$ = 0,6117, which means that the total weight (G) of the electric bicycle, rider and the battery are with higher importance compared to the second parameter (H) – the height of the battery position;
- the coefficient b_{12}=0,8587 , that shows the combined effect of two input factors has value commensurate of the value of the second coefficient b_2 and higher by absolute value;
- the signs of the square coefficients (b_{11} и b_{22}) are alternative which means that with the increase of the value of the first factor the value of the lateral deviation increases and vice versa with the increase of the second factor the value of the deviation lowers.

In the programming code with separate module was checked the importance of each coefficient and the adequacy of the model as in both cases we have used the criterion of Ronald Fisher (1857-1936) [1].

In the check of the coefficient importance are calculated the parametric values of the model excluding the minimal by absolute value coefficient (b_1^2=0,54). The calculated value

$$F = 0,56 < F_{\alpha=0,05;K1=1;K2=8} = 5,32$$

shows that all of the coefficients in the model are significant for the proper calculation of the value.

Comparing the average value of the empirical results (Y_{Ei}) reported during the experiment and the average value of the parametric model values (Y_{Mi}) is another proof of the adequacy of the model, because the calculated value of the Fisher's criteria is lower than the one from the table.

$$F = 0,87 < F_{\alpha=0,05;K1=1;K2=8} = 5,32$$

The same program code was used to create the graphical representation of the model, shown on figure 2.

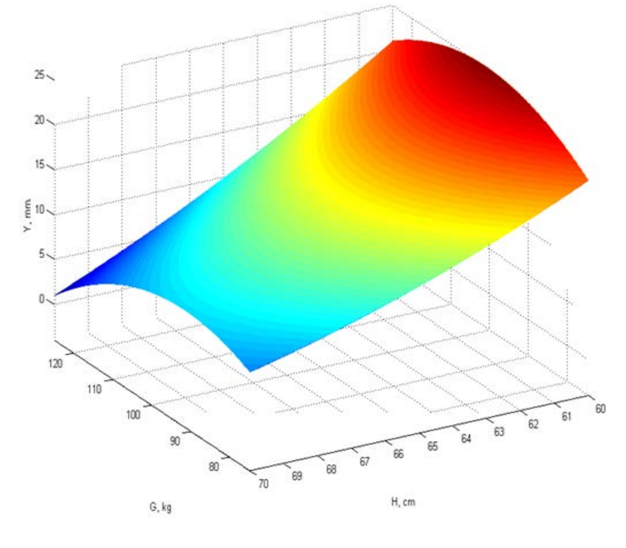

Fig. 2. Graphical representation of the mathematical-stochastic model

The minimal values of Y (minimal lateral vibration deviation of the electric bicycle) is calculated with the following combination of the factor values $G=G_{max}$ (total weight of 125 kg for the electric bicycle, the rider and the battery) and $H=H_{max}$ (the maximal height of the battery position during the experiments of 70 cm).

As a result it becomes clear that the higher position of the battery (H_{max} = 70 cm) measured according to the terra, combined with movement with constant speed(in this case 15 km/h), leads to lower values of the lateral vibration deviation which proves the analogy with the inverted pendulum system.

3. Conclusion

The result of this study proves the thesis that the higher placement of the battery is recommended for better stability and dynamic behavior while cycling with higher speed. It is assumed that the cyclists who ride with higher speed are more experienced in general and will be able to easily overcome the processes of starting and stopping where the lower speed and the higher mass center are precondition for lower stability. At the same time for customers who are expected to ride the bikes with lower speed, for example elders and children, it is recommended the battery to be placed lower and provide an extra stability while starting and stopping the movement.

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The authors of this article are happily obliged to evince their gratefulness to the management of SRS at TU-Sofia for the funding in 2012 г. of the project № 121 PD 0008-05 on the topic „Research of the dynamic stability of electric bicycles“.