AN APPROACH TO VEHICLE RESEARCH

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1. INTRODUCTION

With the advent of the first vehicle on the road there were also some problems of its use and, thus, the requirements for design and performance improvement. In today's conditions, the customers and legislation force the stringent requirements to manufacturers of motor vehicles. In light of these requirements, the two main objectives may be pointed out: 1) to increase the efficiency of vehicle use through increased productivity, 2) to increase safety while using the vehicle. In this sense - to define, investigate and optimize the structure and performance of the vehicle relevant to its quality.

The requirements outlined above are often contradictory and demand compromise solutions. For example, a request to increase the speed of movement in order to increase the productivity of the transport task is contradictory to requirements of a stable and safe movement. In addition, the increase in speed of movement leads to increased mechanical and thermal loads on the parts and components of the vehicles, loads on the driver, the environment and, particularly, road. Another indicator of the productivity of the transport task is a useful payload. Request for increasing the vehicle payload leads to increase of gross vehicle weight that exerts a complex effect on the relevant performance. Vehicles performance is in relation with its structure, design parameters and interaction with the environment [7], [11].

When carrying out the transport task, the vehicle is exposed to road roughness, aerodynamic environment and the effects of the driver control. The results of these disturbances are dynamic processes, which, depending on the research objectives, can be considered independently or coupled in the reference planes of the longitudinal, vertical and lateral dynamics [10]. Increasingly stringent requirements for improvement of motor vehicles performance lead to an increasing share of the active control components for drive regimes and work processes [3]. This extends the basic structure of the vehicle and significantly affects the mechanical and functional couplings in comparison to the classical concept of construction.

Trends in the development and improvement of vehicle design follow the trends of the development of theoretical and experimental research methods at all stages of vehicle life cycle, from development, design, production, use, to recycling. Vehicle domain research is a typical example of interconnectedness and interdependence between theory and experiment. Namely, the theoretical studies of dynamic processes based on the vehicle modeling are good basis for design of the appropriate experimental systems, then for creation of identification models or processing and interpretation of experimental results. On

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the other hand, mathematical modeling and simulation of the dynamic processes of the vehicle are caused by the knowledge on the input data from previous experiments on similar objects, prototypes and on the appropriate databases. In addition, the dependence between the mathematical simulation and the experimental study demonstrates the need to verify the structure and parameters of used simulation models. In addition, a matter of choice of the reference level for verification of research results is always part of the problem.

New opportunities offered by the intensive development of numerical methods, computer technology, electronics and their relevant disciplines are a growing challenge and encouragement in the creation of modern methods for vehicle research based on an efficient combination of theory and experiment. Realizing the importance of solving the above-mentioned problems and following the trends in this area, an approach to explore the dynamic characteristics of the vehicles based on simultaneous use of the results of modeling and experiments is presented in this paper.

PAPER OBJECTIVE AND USED METHODOLOGY

This chapter highlights the general remarks and a short review regarding the formation of the model.

Based on the discussion in the previous section, it can be concluded that the two main segments of vehicle research, both theoretical and experimental, are each coupled in some way to the combined classical approach to their use. A number of serial, parallel and feedback connections can be made between them, to adjust the stages of work, but not in the time course of the individual stages. However, in terms of increasing the efficiency of the vehicle research, which means to use the advantages and eliminate the disadvantages of afore mentioned segments, it is advisable to implement them, ie. to combine them simultaneously in real time (online proceedings). This method of achieving a number of positive effects, such as: 1) ability to determine immeasurable or difficult measurable variables, 2) significant simplification of the simulation model and the experimental system, 3) increase of accuracy of the previously obtained results through iterative determination of reference levels for verification of the results, 4) reduction of research costs, 5) creating the database and the conditions for the expansion and upgrade of the basic structure of the vehicle passive components, 6) introduction of active control, 7) formation of virtual sensors and interfaces of GPS and INS systems, 8) revitalization of previously performed experiments in terms of efficient use of the obtained results.

Models

The general problem of combining mathematics (simulation) and experimental research of vehicles in order to achieve some of the goals stated above, is reduced in this chapter by working on specific problems of vehicle dynamics and its interaction with the environment, expressed in terms of lack of information, input data for modeling and simulation, as well as the difficulties of measuring these data. In order to highlight and solve the task, a physical model of the vehicle was created and shown in Figure 1a).

In general case, a two-axle vehicle with four wheels and four tracks is presented as a spatial physical model with five masses: sprung mass, M, and four unsprung masses, m11, m_{12}, m_{21}, m_{22}, and a total of ten degrees of freedom, x, z , y, θ, ψ, ε, z_{11n}, z_{12n}, z_{21n}, z_{22n}. Characteristics of stiffness and damping of suspension are marked by c_{ij}, k_{ij}, i = 1,2, j = 1,2, respectively, and characteristics of stiffness and damping of the tire by c_{ijp}, k_{ijp}, i = 1,2, j = 1, 2, respectively .

Potential properties of excitation effects of the environment on a vehicle are marked by vectors as follows: N - the uneven road, F - by changing the conditions of adhesion, A - from the air environment, V - from the effects of the driver control. In doing so, a distinction is made between the term of "potential properties of excitation effects ..." and the term "realized excitation interaction between the vehicles and the environment, ie. with a driver". A simple explanation for this is found in an example of excitation of vehicles from road roughness. The potential characteristics, in this case, are actual macro- and micro-roughness of the road, and the excitation resulting from the interaction between the road and the vehicle is carried out in the course of the movement, which is affected by numerous factors. The main problem is that it is difficult to directly measure the properties of the potential and realized excitation of the environment on the moving vehicle. These issues can be discussed and resolved based on the vehicle oscillatory model shown in figure 1a), with the use of an adequate algorithm, the method of combined research shown in Figure 1b), obtained by synthesis of following mathematical model, presented in the state space:

$$\begin{aligned} \dot{x} &= [A]x + [B]r \\ y &= [C]x + v \end{aligned} \tag{1}$$

$$\dot{x} = [A_i]x_i + [B_i]w \tag{2}$$

$$\begin{aligned} \dot{x}_p &= \lfloor A_p \rfloor x_p + \lfloor B_p \rfloor r \\ y_p &= [C_p]x_p + v_p \end{aligned} \tag{3}$$

Equation (1) represents the state space mathematical model for the determination of the state vector, x, and output vector, y, of the vehicle, where r - is a vector of excitation due to road roughness and v - a vector of immeasurable inputs. Equation (2) represents a mathematical model of the implements involved in the structure of the vehicle in terms of improving performance, or in an experimental system in terms of expanding the measurement capabilities, while equation (3) shows a mathematical model of the extended system with the included structure models of vehicles, implements and estimators.

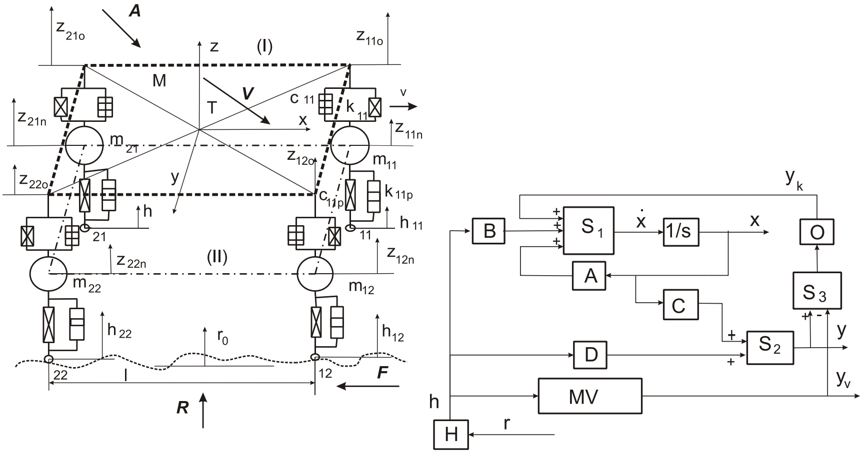


Figure 1 a) Vehicle simulation model, b) Block diagram of the extended system "vehicle – simulation model – estimator"

Block diagram of the algorithm of the research method used in this study is shown in figure 1b). As noted above, the method is based on the iterative use of the simulation results of the vehicle mathematical model and the experimental results obtained on the vehicle for which that model is formed. Thus, the observed complex couplings between the blocks in figure 1b) represent the structure of an integrated system of vehicle - a simulation model vehicle - estimator of state variables and parameters. Designations in figure 1b) are: A - dynamics matrix, B - matrix interface of inputs, C - matrix interface of output and state variables, D - matrix interface of inputs and outputs, MV - real vehicle as measuring object, O - observer, as a component estimator, x - state vector, h - vector of excitation due to road roughness, y - vector of outputs of the simulation model, y_v - vector of measured outputs of the real vehicle, y_k - output vector from the observer. Within this generalized block display, the structure, parameters and iterative procedure estimators are not specified in detail, but only the basic contours of the couplings between basic components, vehicle - model - estimator. A detailed specification is given in the selection of a particular type of estimator and its formation depending on research task and set of demands [2].

Experimental systems

For experimental research, two experimental passenger vehicles were used, marked as “vehicle 1” and “vehicle 2”, respectively. Details of the measuring points on the “vehicle 1” are shown in figure 2, in the following order: a) vertical acceleration sensor of front left wheel unsprung mass (set of four identical sensors on all four wheels), b) three-axis acceleration sensor placed on the engine mount, c) dynamometric steering wheel with sensors to measure the angle, angular velocity and torque on the steering wheel. In figure 2d), a detail of connection of the vertical acceleration sensor to the right rear wheel of the “vehicle 2” is shown.

a) *b)* *c)* *d)*

Figure 2 Measurement devices on the experimental “vehicle 1”: a) acceleration sensor on the front left wheel, b) three-axis sensor on the engine mount, c) sensors on the steering wheel, on “vehicle 2”, d) acceleration sensor at the rear right wheel

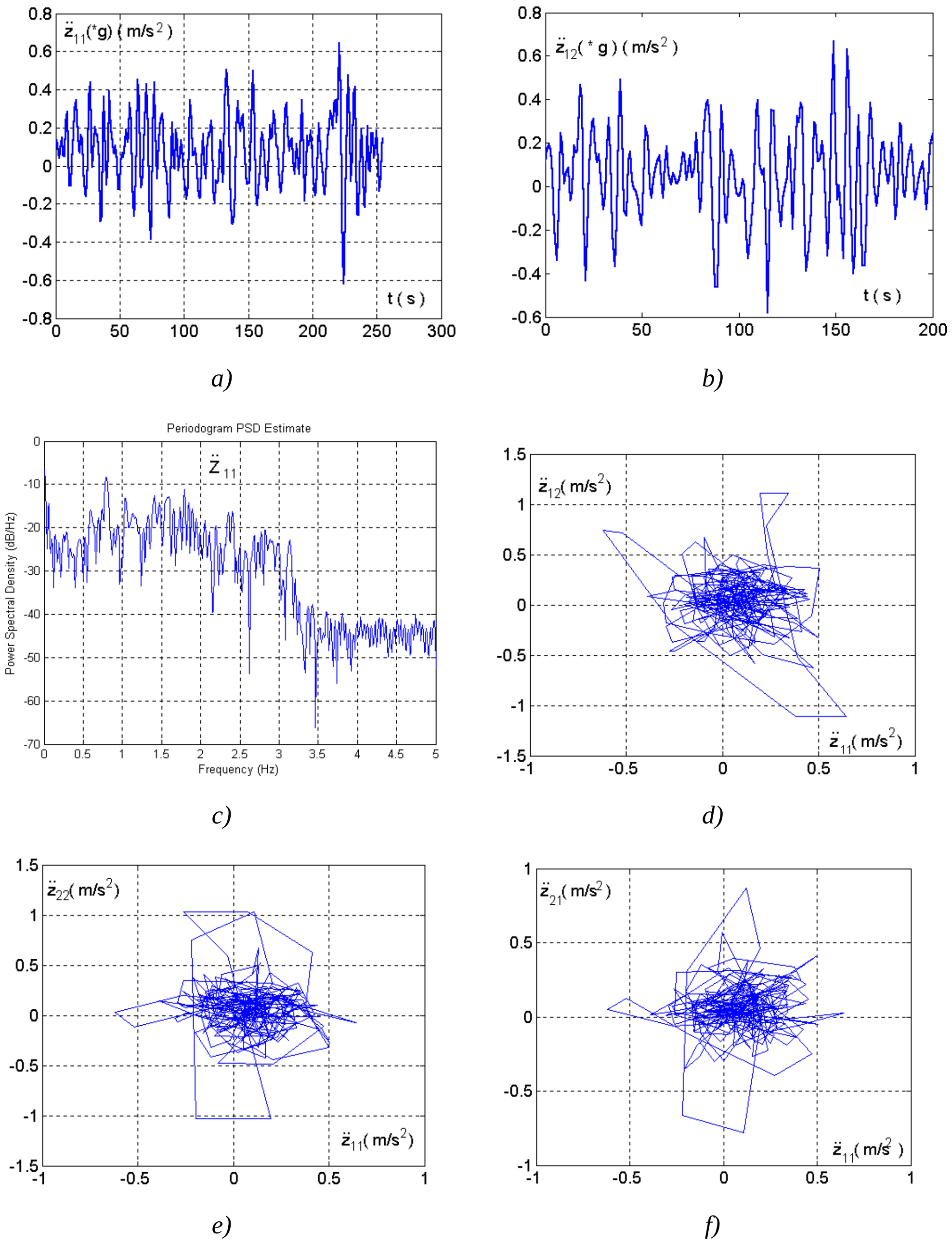
Figure 3 shows the testing “vehicle 1” in conjunction with a measuring device for recording the characteristics of road roughness [9] and details of this measuring device platform with vertical acceleration sensor on the experimental stand in the laboratory.

Figure 3 Two single axle trailers for road profile measurement on the experimental stand and towed by experimental “vehicle 1”

RESULTS

As pointed out, the proposed methodology presented in the previous chapters is applicable to different segments of the research of vehicles and engines, as well as of the structure, dynamics, identification, diagnosis, control, optimization, etc. However, starting from the formed vehicle models in the previous chapter and conducted research in the context of the present work, the results of this chapter are related to oscillatory processes caused by the interaction between the vehicle and the road roughness. In order to present the efficiency of the proposed methodology, the simulation model of the vehicle, shown in figure 1a), can be reduced to equivalent models in accordance with the modes of movement and dominant dynamics levels (longitudinal, lateral, vertical) or broken down into a number of sub-models, depending on the specific problem being emphasized.

Some illustrative results of this study are shown in figures 4 to 6:



a) *b)*

c) *d)*

e) *f)*

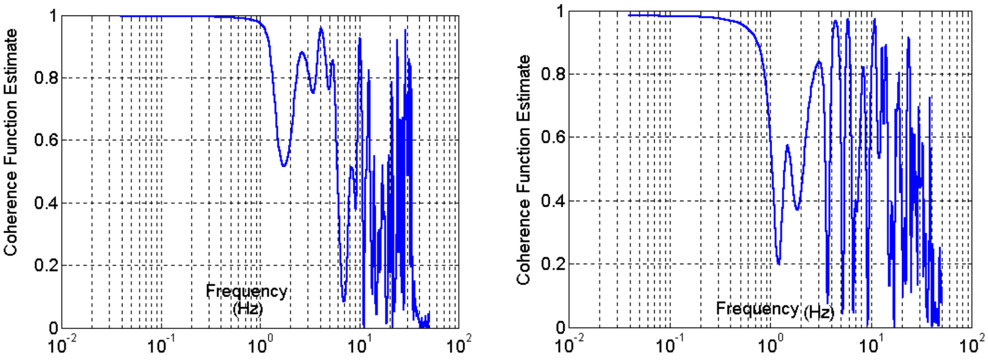
Figure 4 a), b) time records of vertical acceleration of the front wheels of "vehicle 1", c) the power spectrum density of the front left wheel vertical acceleration, d), e), f) mutual dependence between the front left wheel vertical acceleration and vertical acceleration of the front right wheel, the rear left wheel and the rear right wheel, respectively

The time records in figure 4a), and 4b) indicate random nature of the vertical acceleration which is in accordance with road excitation random properties. An approach was used for signal processing and preceding data presentation. Namely, the time records were used for estimation of corresponding spectral characteristics. The three algorithms were used to realize this objective [1], [5], [7]:

$$\begin{aligned} &S_{\ddot z}(f)=\lim(1/T)[\ddot Z_T(f)]^2,\, T\to\infty,\ \ S_h(\Omega)\approx S_{\ddot z}(f)v(2\pi)^{-5}f^{-4},\\ &\log S_z(\Omega)=\log S_z(\Omega_0)+w(\log\Omega_0-\log\Omega) \end{aligned} \qquad (1)$$

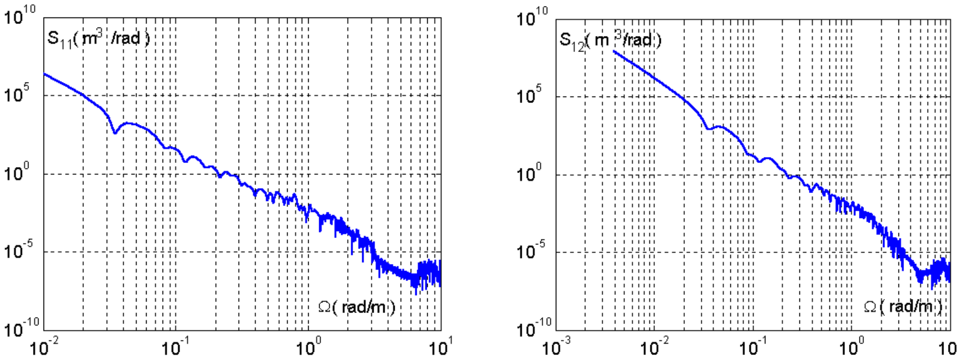
where: $Z_T(f)$ is a spectrum of the wheel centre vertical acceleration complex amplitude, $S_z(f)$ is corresponding power spectrum density, $S_z(\Omega)$ is excitation spectrum of road roughness estimated by above given inverse method, and w, Ω_0 are parameters of road excitation spectrum.

Figure 6 shows these spectra for all four wheels of the “vehicle 1”. The shapes of these curves and the estimated parameters confirm the hypothesis of homogeneity and isotropy of the road surface given in papers [4], [6], [8]. The results shown in figure 4d), 4e) and 4f) indicate wheels excitation dependence in time domain, while, in figure 5, dependence in frequency domain is shown. The frequency content of the measurement record from figure 4a) is presented in figure 4c).

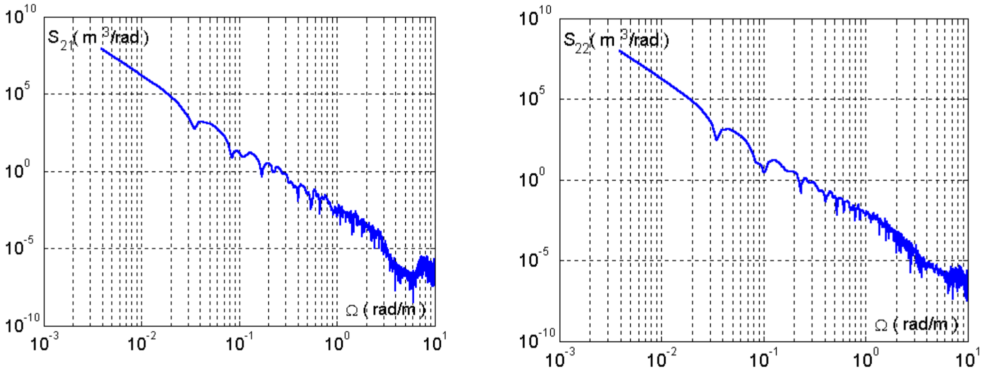


a) *b)*

Figure 5 Coherence functions between: a) front wheels, b) front left wheel – rear left wheel



a) *b)*



c)

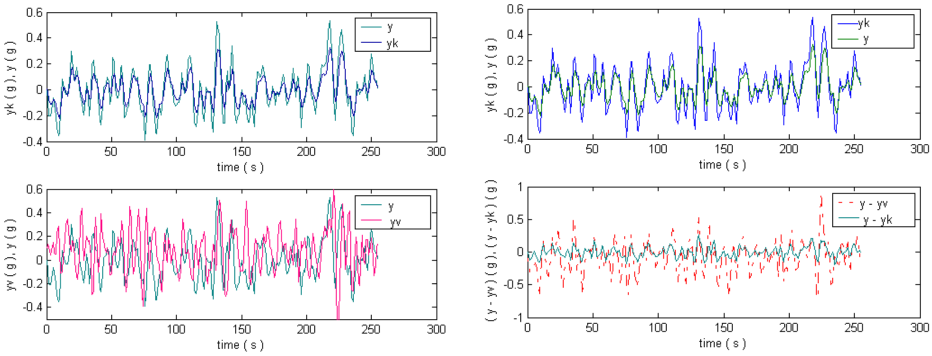
d)

Figure 6 Excitation spectrum of the front wheels: a) left, b) right and of the rear wheels: c) left, d) right, for: “vehicle 1”, speed 50 kmh^{-1}, the straight-line road section

Previously presented results served as a basis for implementation of procedure shown with algorithms in figure 1b).

In accordance with the structure and physical parameters of the oscillatory model of the vehicle, shown in figure 1a), a quarter model with two masses in the domain of the left front wheel is formed and included in the algorithm of the integrated system for estimation of state variables and the measured outputs of the system in Figure 1b). In addition, the state vector contains five variables as follows: vertical displacement and vertical acceleration of sprung mass, M11, as part of the total mass of the vehicle (M11=M/4), then the vertical displacement and acceleration of unsprung mass, m11, and vertical excitation of front left wheel from road, h11. Vector of the measured output contains one variable - vertical acceleration of the front left wheel, which can be expanded with the vertical displacement of the wheel. In this case, the primary input of the system formally has zero value and the secondary input, as process noise, is defined by the vector of the basic features of the uneven road. These are formed by using the random signal generator of uniform spectral characteristics, then by using the shaping filter and database on identified characteristics of the uneven road, the shape and parameters as in Figures 6a), 6b), 6c), 6d). Other, secondary input of the integrated system is noise measurement contained in the measured output, or the vertical acceleration of the wheel. In the first stage of the procedure, the structure and parameters of the estimator are identified, as a sub-system with two input vectors (measured and simulated output system of the vehicle) and two vector outputs (estimates of the outputs and estimates of the vehicles state space variables). Thus, the procedure can be used to obtain unknown state variables, immeasurable inputs and outputs, increasing the accuracy of the results of simulation and experiment.

For the basic data of the “vehicle 1”: total mass of 1235 kg, sprung mass of 1123 kg, wheel base of 2.449 m, wheels tracks of 1.3 m, coordinates of the centre of mass relative to the front axle - 1.13 m and above the ground plane - 0.5 m, and the previously obtained results in this paper, a quarter simulation model of the front left wheel with suspension and a quarter of the vehicle mass was formed. This model is included in the extended system shown in Figure 1b), with Kalman filter as estimator, and then the research is conducted in accordance with above presented algorithm of iterative combination of simulation and experimental results. The illustrative examples of these results are given in Figures 7a) and 7b).



a) *b)*

Figure 7 Estimates of the vehicle front left wheel vertical acceleration:

a) yv – measured output, yk – filtered output, y – true output, b) yk – filtered output, y – true output: y – yv – measurement error, y – yk – estimation error, experimental "vehicle 1", asphalt road, speed 50 kmh^{-1}*, Cov(y–yv)=0.0689, Cov(y–yk)=0.0070*

In figure 7a) below, the measured time history of the vertical acceleration of the front left wheel and its true value are compared and, in the same picture above, the filtered and the true value of this variable are compared. Figure 7b) below shows measurement and estimation error, respectively, and figure 7a) above shows the comparison between the filtered and true value of the left wheel vertical acceleration. The efficiency of the implemented estimation procedure for example given above is evaluated by mutual flow graphics – qualitative and their numerical indicators - quantitative. One such indicator is the error covariance - value of 0.0689 is obtained for measured series, as measurement error, value of 0.0070 for estimation series, as estimation error (values given in figure 7b) below). This shows that the used estimation procedure has significantly increased the accuracy of the previously measured results.

CONCLUSIONS

Combining the theoretical and experimental methods in an appropriate manner can significantly improve the efficiency of vehicles research. The special contribution is to make modern methods of identification of dynamical systems and methods for estimation of state variables and parameters of the system. Optimally chosen structure of an extended system with estimator provides a number of positive effects, such as: ability to determine immeasurable or variables difficult to measure, significant simplification of the simulation model and the experimental system, increase of the accuracy of the previously obtained results through iterative determination of reference levels for verification of the results, creating the database and the conditions for the expansion and upgrade of the basic structure of the vehicle passive components, introduction of active control, revitalization of previously performed experiments in terms of efficient use of the obtained results. One example of increasing accuracy of the previously obtained experimental results using the proposed estimation algorithm is presented in this paper.

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