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СЕКЦИЯ "*ТЕХНИКА & ТЕХНОЛОГИИ*"

SECTION "*TECHNICS & TECHNOLOGIES*"

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EXPERIMENTAL RESEARCH OF INTERACTION BETWEEN THE STEERING SYSTEM AND THE SUSPENSION SYSTEM OF A PASSENGER CAR

ЭКСПЕРИМЕНТАЛЬНО ИССЛЕДОВАНИЕ ВЗАИМОДЕЙСТВИЯ МЕЖДУ СИСТЕМОЙ УПРАВЛЕНИЯ РУЛЕМ И СИСТЕМОЙ ПОДВЕСА ПАССАЖИРСКОГО АВТОМОБИЛЯ

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Abstract: *Mechanical and functional couplings mutually connect motor vehicle's systems. The coupling between the steering system and the suspension system is especially important from the aspects of vehicle's turnability, stability and dynamics. A review of relevant literature shows that interaction between the steering system and the suspension system has frequently been considered theoretically. As for experimental research, there are few results of laboratory tests, while the results of road tests are rarely available. In this paper, a method for experimental road investigation of interaction between the steering system and the suspension system of a passenger car is developed. The car is considered as a system with several inputs and several outputs. The major part of the paper belongs to processing and interpretation of experimental data. The results of spectral and correlation analyses of acquired data are presented in the paper.*

***KEYWORDS**: EXPERIMENTAL RESEARCH, STEERING SYSTEM, SUSPENSION SYSTEM, PASSENGER CAR*

1. *Introduction*

Phenomena related to some aspects of interaction between the steering systems and the suspension systems of motor vehicles have been observed since 1930's. Review and analysis of available literature imply that a small number of older papers, as [1-8], deal directly with interaction between mentioned systems. Investigations carried out in the papers included independent front suspension systems (McPherson, double arm) combined with the rack-and-pinion steering system. Research accent has been predominantly put to distinguishing the influencing parameters of the suspension system and steered wheels on appearance of vibrations in the steering system, and to possibilities for reducing the steering system vibrations. Conversely, influence of the steering system on the suspension system has not been investigated in detail. Most frequently, authors had derived detailed mechanical models of the tires, the suspension systems and the steering systems. Differential equations of motion were set and solved, based on the lows of analytical mechanics, but analytical considerations had rarely been followed by experimental research on the test bench or at the moving vehicle.

In recent literature, as [9-12], there are detailed dynamical models of the rack-and-pinion steering system combined with McPherson suspension system. Hence, this paper will not deal with development of mathematical-mechanical models of the two systems, but with development of the model for identification of the dynamic structure of the vehicle from the aspect of interaction between the two mentioned systems. Thereby, inputs and outputs of developed models must be correlated to quantities acquired during corresponding experimental tests.

Experimental research of interaction between the steering system and the suspension system [12] contained two main test types – laboratory tests and road tests. Laboratory tests included the turning of the steering wheel with vehicle standing (static regime) and slowly moving (parking regime) on different pavements and introduction of unit impulse into the steering and the suspension systems through the wheels (overcoming an obstacle in the shape of "step" and "ramp"). Road tests involved driving on different roads, in a straight line or in curves, with constant and variable speed. Measuring quantities were chosen in such a manner to represent inputs and outputs of the steering and suspension system of the vehicle. Test results were analyzed in time domain and in frequency domain with the use of spectral theory (conditional spectral analysis) and the non-parametric identification of frequency responses of transfer channels [13].

2. *Method of research*

Methods of research of interaction between the steering system and the suspension system of a car are not standardized. For the purpose of this research, a method was designed, according to research objectives and available measuring equipment.

Experiments were conducted on "ZASTAVA FLORIDA 1.3 EFI" vehicle, a passenger car that has a combination of rack-and-pinion steering system and McPherson front suspension system, common to almost all "ZASTAVA" cars. Due to available space, only part of the results of the road tests are presented and analyzed in the paper.

2.1. *Measured quantities*

The following quantities were measured, according to the objective of the research:

- steering wheel torque, M_v,
- steering wheel angular position (angle), β_v,
- relative deformations of front left wheel tie-rod in 0/45°/90° directions, ε_1, ε_2, ε_3, respectively,
- vertical acceleration at the center of the front left wheel, $\ddot{z}_1$,
- vertical acceleration at the center of the front right wheel, $\ddot{z}_2$,
- vertical acceleration at the center of the rear left wheel, $\ddot{z}_3$,
- vertical acceleration at the center of the rear right wheel, $\ddot{z}_4$,
- vertical acceleration at the point where the front left damper is connected to the fender, $\ddot{z}_A$, and
- longitudinal speed of a sprung mass of the vehicle, $\dot{x} = v$.

2.2. *Necessary equipment*

Steering wheel torque and angular position are measured using a dynamometric steering wheel shown in Figure 1. This, special, steering wheel has four strain gauges connected into a full Wheatstone bridge to measure steering torque and a potentiometer to measure steering wheel angular position.

Relative tie-rod deformations are measured using two miniature strain gauge rosettes, Figure 2a/ (one active, number 1 in Figure 2a/, the other compensative, number 2 in Figure 2a/), each having three strain gauges positioned in 0/45°/90° directions in relation to tie-rod's longitudinal axis.

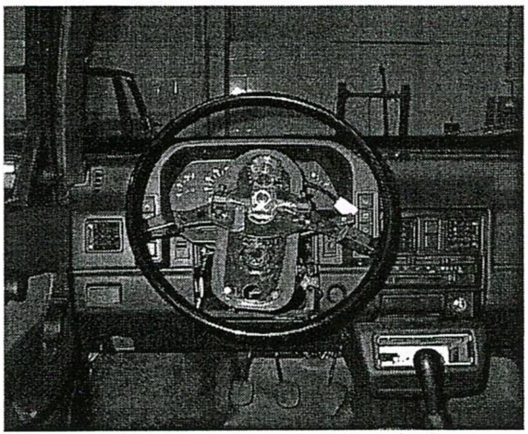
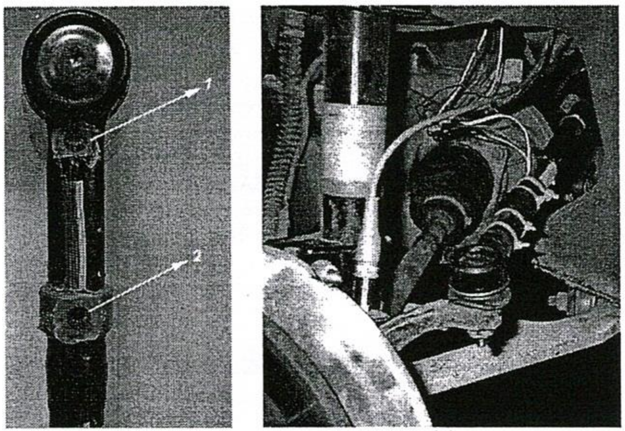


Fig. 1 *Dynamometric steering wheel*

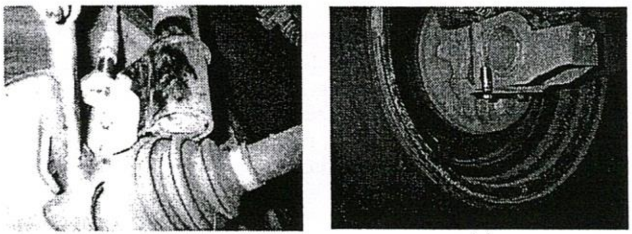
Rosettes are carefully sealed and protected from external influences with insulating tape, Figure 2b/. One strain gauge from the active rosette and one strain gauge from the compensating rosette are connected into a half-bridge circuit. Thus, three channels of measuring bridge obtain information on tie-rod's strain in 0/45°/90° directions. Stress is additionally calculated according to known equations.



a/ b/

Fig. 2 *Installation of rosettes for measurement of tie-rod's relative deformations*

Inductive acceleration transducers measure vertical accelerations at the centers of all four wheels. These accelerations are measures of road's influence on the wheels. Transducers are mounted on additional brackets, Figure 3. It is important to mount them as close to the wheel's centers as possible, i.e. to connect them to wheel hub and place them in vertical position. Term "vertical" should be conditionally understood in this case, as transducers are firmly connected to the wheel hubs and their motion is not strictly vertical. However, since variations in camber and caster angles are small, influence of measurement direction is negligible. It is also important to ensure that resonant frequencies of the brackets are in the area above the frequency range significant for analysis of experimental data.



a/ b/

Fig. 3 *Installation of acceleration transducers at centers of the front wheels (a) and the rear wheels (b)*

Acceleration transducer, that measures vertical acceleration at the point where front left damper is connected to corresponding fender, has a special support, Figure 4. Transducer's bracket is firmly connected to damper's support.

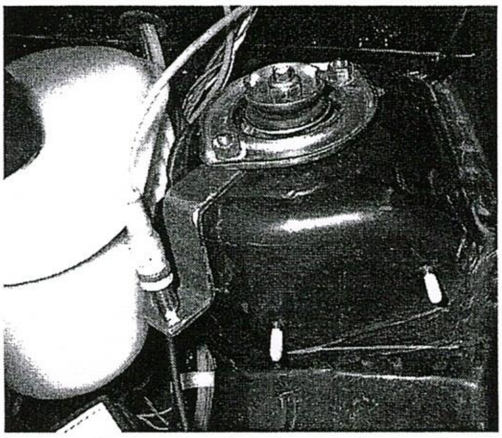


Fig. 4 *Installation of acceleration transducer at the point where the damper is connected to the fender*

Correlation-optical speed transducer, Figure 5, measures longitudinal speed of the sprung mass of the vehicle.

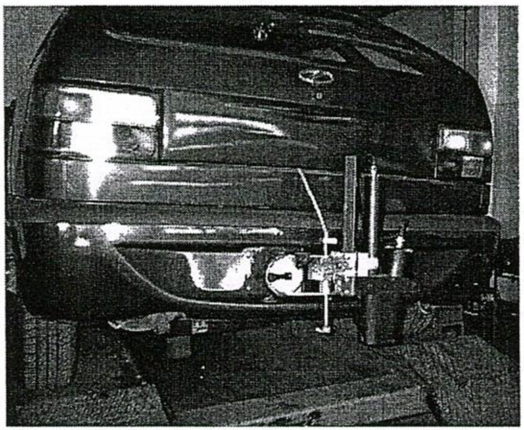


Fig. 5 *Installation of correlation-optical speed sensor*

2.3. Road test regimes

Research plan anticipated several different road test regimes:

- straight line drive with different constant speeds on different roads,
- curvilinear drive at different constant speeds on different roads,
- quasi-harmonic turning of the steering wheel during constant speed drive on linear road section,
- full left turn and full right turn of vehicle during constant speed drive and
- general case of curvilinear, variable speed drive.

2.4. Data acquisition and processing

Conducted experimental research on vehicle in road conditions have had the objective to establish the influence of vehicle speed, type of the road and the shape of the road on interaction between the steering system and the suspension system. Tests were conducted during constant speed driving and variable speed driving. Different roads included: macadam roads, concrete roads and asphalt in good, medium and bad condition. Test tracks were linear and curvilinear. Data sampling rate was 100 [Hz] and each test lasted for 30 [s]. Since time records give only basic information on the scope of strain or accelerations that act upon structures of the steering system and the suspension system of the vehicle at each road test, additional spectral signal analysis and comparison with other analyzed data were performed. In this paper, only results of tests performed during constant speed drive along a curvilinear road are presented and analyzed.

Models of the vehicle shown in Figure 6 were used for processing of experimental data acquired during curvilinear drive with constant speed. General model, Figure 6a/, has six inputs and two outputs. The inputs are: spectra of vertical accelerations at the centers of all four wheels, $\ddot{z}_i(f) = X_i$, $i = \overline{1,4}$, spectrum of steering wheel torque, $M_v = X_5$ and spectrum of steering wheel angle, $\beta_v = X_6$. The outputs are spectrum of vertical acceleration at the point where front left damper is connected to the fender, $\ddot{z}_A(f) = X_7$ and spectrum of normal stress in tie-rod's cross-section, $\sigma_{sp}(f) = X_8$. Decoupling of the inputs and decomposition of the model into two equivalent models [14] having six decoupled inputs $X_{i \cdot j!}$, $i=1,\dots, 6$, $j=1,\dots,5$, and only one output give the models shown in Figure 6b/ and Figure 6c/. Noise spectrum at output X_7 is denoted with N_7 and noise spectrum at output X_8 is denoted with N_8.

Optimal frequency response functions are denoted with L_{ij}, $i=1,\dots,6$, $j=7,8$.

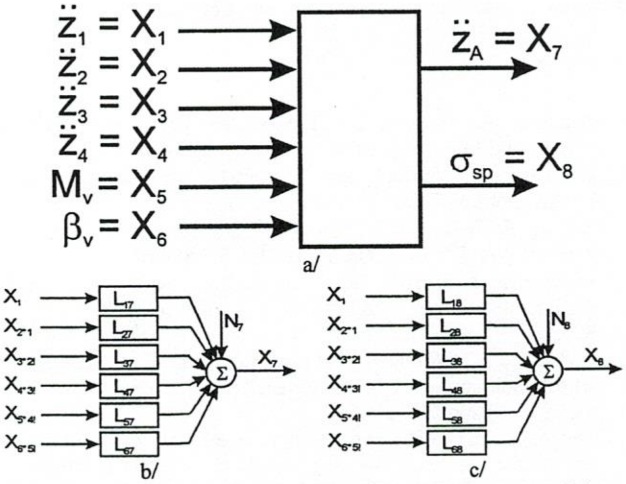


Fig. 6 *Models used for the study of curvilinear constant speed drive*

3. *Results and discussion*

Multiple coherence functions that provide measures of linear dependence between each output and all of the inputs (independent of the correlation among the inputs) for curvilinear drive with constant speed of v = 40 [km/h] are shown in Figures 7 and 8.

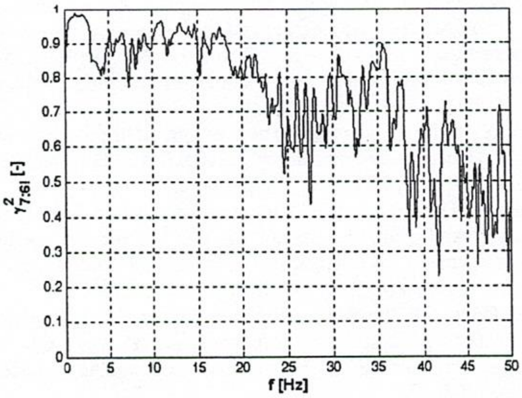


Fig. 7 *Multiple coherence function between the output X_7 and all of the inputs*

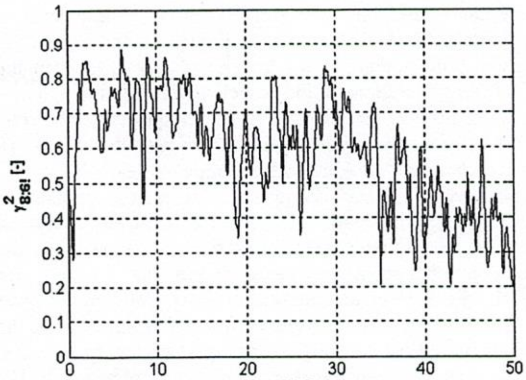


Fig. 8 *Multiple coherence function between the output X_8 and all of the inputs*

Multiple coherence function between the output – vertical acceleration at the connection point between front left damper and fender, Figure 7, has high values for frequencies smaller then 35[Hz]. Sufficiently high values of multiple coherence function imply that the model is well defined. Similar conclusion is valid for multiple coherence function between the output – tie-rod's stress and all the inputs, Figure 8.

Figures 9 and Figure 10 show the influence of vehicle speed on frequency response functions for the two outputs and the most influential input – vertical acceleration at the center of the front left wheel. Smaller speed give greater intensity of frequency response functions in a whole frequency scale.

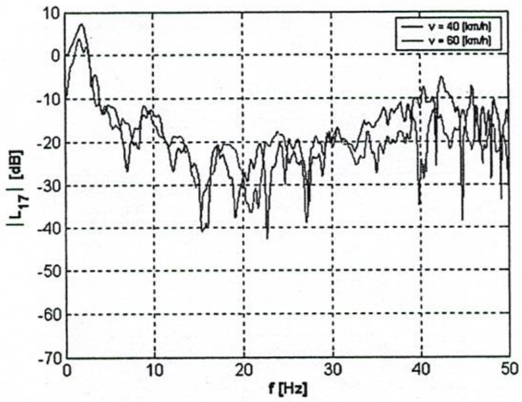


Fig. 9 *Influence of vehicle speed on frequency response functions for curvilinear constant speed drive (asphalt road of medium quality, transfer channel $X_1 \rightarrow X_7$)*

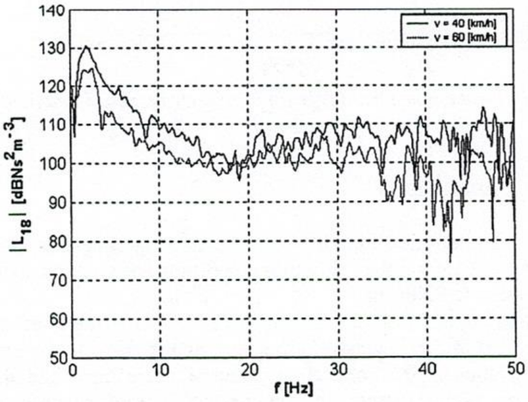


Fig. 10 *Influence of vehicle speed on frequency response functions for curvilinear constant speed drive (asphalt road of medium quality, transfer channel $X_1 \rightarrow X_8$)*

The influence of the type of the road on the intensities of the frequency response functions for the model of curvilinear constant speed (60 [km/h]) drive is illustrated in Figure 11 and Figure 12. This influence is more distinct for transfer channels between the inputs – vertical accelerations at the wheel centers and the output – normal stress in tie-rod's cross section. Better quality of the road enhances the influence of these inputs to the output. Above 10 [Hz], transfer channel "steering wheel angle – tie-rod's normal stress" shows inverse effects – better road lessens the intensity of frequency response function. At transfer channels "vertical accelerations at the wheel centers – vertical acceleration at the connection point between the damper and the fender", for frequencies below 8 [Hz] and above 30 [Hz], better roads give higher intensities of frequency response functions. Inputs from the steering wheel do not have enough intensity at higher frequencies, so conclusion regarding their transfer channels cannot be reached in the same manner.

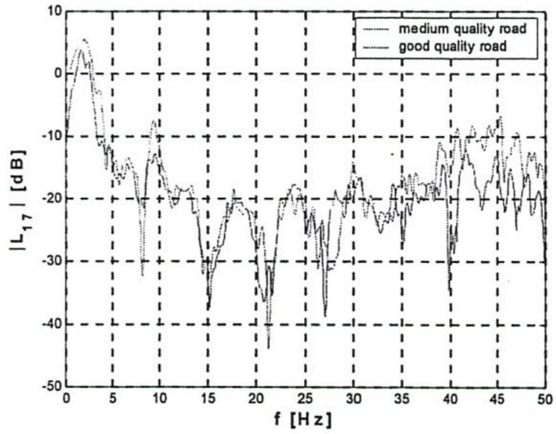


Fig. 11 *Influence of the road type on frequency response functions for transfer channel* $X_1 \rightarrow X_7$

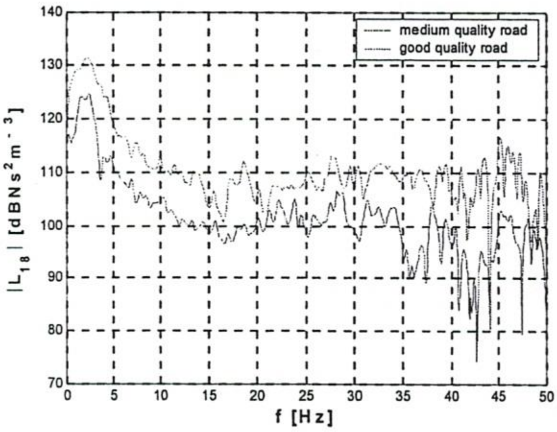


Fig. 12 *Influence of the road type on frequency response functions for transfer channel* $X_1 \rightarrow X_8$

4. *Conclusions*

Road tests of interaction between the steering system and the suspension system of the car during constant speed drive have demonstrated the following:

- System inputs, vertical accelerations at the centers of all wheels show an intensive influence on the outputs (vertical acceleration at the connection point of the damper and the fender; normal stress at the tie-rod's cross section) at frequencies below 10 [Hz]. The intensity of the frequency response functions depends on physical distance between the corresponding input and output. The most intensive influence shows the vertical acceleration at the center of the front left wheel.
- Vehicle speed also has influence on the intensity of frequency response functions. The increase of speed during driving on the same road type decreases the intensity of frequency response functions.
- The type of the road also shows the influence on the frequency response functions. Worse roads decrease the influence of the inputs to the outputs and bring noise and nonlinearities to the system.

Experience gained during the research has pointed out the possibilities for improvement of the formed method. Used experimental installation should be complemented with additional transducers for measurement of: the right tie-rod's load, the loads of springs and/or dampers (indirectly gained here) of both front wheel suspension systems and longitudinal acceleration and lateral acceleration of the car. Parametric identification methods should be used for data processing and identification of the dynamic system of the vehicle from the aspect of interaction between the steering system and the suspension system. Several tests with variable speed of the vehicle should be conducted. Introduction of non-stationary motion of the vehicle needs involvement of the theory of random non-stationary processes, the ways of their interpretation and processing of acquired data, because necessary procedures for the analysis of non-stationary processes are significantly more complex.

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