



Oleg VLADIMIROV

**RESEARCH OF BRAKING PROCESS
OF TRANSPORT VEHICLE WITH HYDRAULIC
BRAKE SYSTEM PARAMETERS**

**Summary of Doctoral Dissertation
Technological Sciences, Transport Engineering (03T)**

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Vilnius  **2005**

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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The dissertation will be defended at the public meeting of the Council of Scientific Field of Transport Engineering in the Senate Hall of Vilnius Gediminas Technical University at 10 a. m. on 8 December 2005.

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Oleg VLADIMIROV

**LENGVOJO AUTOMOBILIO SU HIDRAULINE
STABDŽIŲ SISTEMA STABDYMO PROCESO
PARAMETRŲ TYRIMAS**

Daktaro disertacijos santrauka
Technologijos mokslai, transporto inžinerija (03T)

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1. General Characteristic of the Dissertation

Topicality of the problem

Vehicle-based safety strategies generally fall into two categories: *Crashworthiness* – designs and technologies that help to mitigate the injury potential of a crash (sometimes called "passive safety"); *Collision avoidance* – technologies designed to help the driver in avoiding potential crashes (sometimes called "active safety").

Crash avoidance technologies are intended to assist road users to avoid potential collisions under various adverse environmental or operating conditions. The tyres and brake systems are taking the first place in active safety raw, as the crash statistic shows. That's why the investigation of these systems has a high importance for the vehicle active safety.

The modern hydraulic brake system consists of various functional systems and elements such as ABS, EBD, cylinders, electromagnetic valves, filters, pipelines, microprocessors and etc. The processes, occurring in these systems, quickly varied, i.e. speed and pressure of fluid quickly vary in time. The speed of a sound in hydraulic system is much greater, in comparison with the speed of a sound in the pneumatic system, therefore the dynamic processes in hydraulic system occur much faster. But if some air occurs in hydraulic system, the dynamic characteristic of it is rapidly changes. The account of physical processes in hydraulic systems, depending on properties of the system and fluid, has the importance evaluating reliability of brake systems. It's also very important to know that processes are there in the system when any mode of failure occurs (such as the leakage of system and etc).

Aim and tasks of the work

The objective of the research work is to investigate the braking process of the vehicle with hydraulic brake system; to expand the possibilities of examination of braking process during traffic accidents' investigation (expertise) and further brake system's scientific research.

For achievement of the results the following tasks were set:

- To analyse the automobile hydraulic brake systems, to find the peculiarities of their application in the research of vehicle braking dynamics.
- To develop the mathematical model of vehicle hydraulic brake system with/without antilock brake system (ABS) components, taking into account physical – mechanical properties of the system and ABS control algorithm.

- To develop the 3D mathematical model of a vehicle with the certain hydraulic brake system and disk brake mechanism taking into account the interaction between the wheel and road surface.
- To carry out natural experimentation of the vehicle with hydraulic ABS brake system in emergency braking, during which to define/indicate the pressure waves in hydraulic system and meanings of main movement parameters of vehicle, such as consistent pattern of deceleration alteration, linear speed of vehicle while the braking process, factual vehicle braking distance and etc.
- To carry out mathematical experimentations of the 3D mathematical model of a vehicle with hydraulic brake system, during which to define:
 - a) meanings of main movement parameters of vehicle: deceleration, linear speed, braking distance, tyre slip, friction and etc.;
 - b) meanings of main parameters of hydraulic system: pressure in different system points, fluid debit and velocity, movement of pistons and etc.

Scientific novelty

The complex mathematical model of 3D vehicle with disk brake mechanisms and hydraulic brake system with ABS was developed. The following things are taken into account in the present model of brake system: distribution of sound waves in fluid, air influence to the speed of pressure waves, fluid interaction with the solid bodies (pistons), module of elasticity of fluid, control algorithm of ABS system and etc. The dynamic models of disk brake evaluate elastic, damping and frictional properties of the pad and the housing. The dynamic model of the 3D vehicle takes the dynamic properties of the suspension and the tyre, the tyre–road friction coefficient, that depends on the longitudinal tyre slip and the linear velocity of the wheel, into account.

Methodology of the research

The theoretical and experimental investigations on vehicle braking parameters are presented in the scientific work. Experimental mathematical investigations were performed by applying analytical mathematical methods. Natural experimentations were performed by applying the following equipment:

- Decelerometer VZM 100, an appliance for measurement of deceleration, together with the software for reading testing results;
- Danfoss fluid pressure transmitters with Analogue/Digital Scope Hameg 1507–3 and the software SP107E, for reading the testing results.

For computerized modelling there have been used novel programmes developed by the author using Maple & Compaq Visual Fortran software packages.

Practical value

The developed mathematical model of vehicle with hydraulic brake system extends the possibilities of investigation of hydrodynamic processes inside the system in emergency braking mode. The more precise meanings of vehicle movement parameters can be obtained from the developed mathematical model and can be used in the context of traffic accidents investigation and in the design and improvement of vehicle hydraulic brake systems.

Assumptions, made in the work, and evaluation

1. The assumptions of hydraulic brake system are:
 - The fluid in the system is viscous and elastic(compressible);
 - The movement of fluid in a hydraulic pipeline is considered as one dimensional and unsteady, i.e. all local speeds are considered equal to the average speed and depend on time;
 - The pressure is considered identical at all points of the cross section and depends on longitudinal coordinate of the pipeline and time.
2. The dynamic model of vehicle with disk brake mechanisms evaluate elastic, damping and frictional properties of the pad and the hosting, takes the dynamic properties of the suspension and the tyre, the tyre–road friction coefficient into account.
3. The tyre–road friction coefficient depends on the longitudinal and lateral tyre slip and the linear velocity of the vehicle.
4. Experimental investigations of the vehicle braking process were carried out on the straight even surfaced non-roughened asphalt-concrete road surface with initial movement speed of 40, 60 and 80 km/h.
5. The pressure of brake cylinders during experimental measurements is considered identical to the pressure sensors' measured pressure.

Defended propositions

- The mathematical model of vehicle hydraulic brake system;
- The mathematical model of vehicle with disc brake mechanisms;
- The meanings of hydraulic brake system's parameters in emergency braking mode;
- The meanings of parameters of dynamic processes of the vehicle during emergency braking.

The scope of the scientific work

The scientific work consists of the general characteristic of the dissertation, 4 chapters, conclusions, list of references and list of publications. The total scope of the dissertation – 103 pages, 62 pictures, 9 tables and 2 addenda.

Acknowledgements

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2. Analysis of Reference Publications

Among the abundant points of view and stages in researching the development in the automobile dynamics field, we have been studying fundamental subjects focusing on the improving automobile dynamic behaviour. Considering the importance of the braking processes, we have been studying the suspensions, hydraulic brake systems, tyres parameters and road characteristics.

Vehicle movement parameters within various situations and different control methods of ABS were investigated in scientific works of numerous scientists, such as: M. Bogdevičius, J. Sapragnas, A. Rutka, V. Mitunevičius, O. Lukoševičienė, O. Prentkovkis, S. Nagurnas, R. Pečeliūnas, S. Drakunov, S. Choi, D.-W. Cho, M. C. Wu, M. C. Shih, R. Freeman, J. Lüdemann, S. Taheri, F. Jiang, J. Yi, J. S. Yu, I. Petersen, T. A. Johansen, V. Ivanov, V. Boutylin, J. Lepeshko and others.

When studying the dynamics of the automobile braking process, the impact of the most important parameters of the braking system on the braking process shall be taken into consideration. This work deals with the automobile three-dimensional model with the hydraulic braking system, the suspension as well as the dynamic processes of the interaction between the wheel and road surface.

Although automobile behaviour during braking has been studied by many authors, most of the investigations have been assuming the simple dynamic models evaluating only suspension and automobile inertia characteristics. Analyses of the influence of driver reaction, hydraulic brake system of automobile, interaction of tyres with surface have rarely been reported.

3. Mathematical Model of Hydraulic Antilock Brake System

In this work automobile hydraulic break system consisting of two contours is considered. The main components of the system are shown on Fig 1.

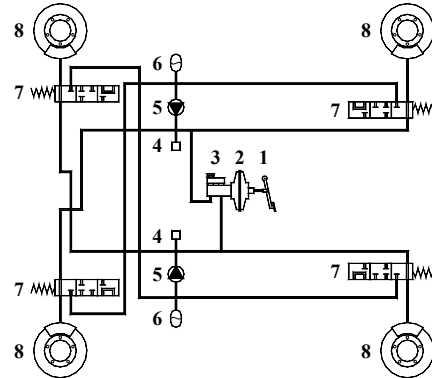


Fig 1. Principal scheme of hydraulic brake system:

1 – braking pedal; 2 – booster; 3 – main cylinder; 4 – dampfer; 5 – pump; 6 – hydraulic accumulator; 7 – electromagnetic solenoid valve; 8 – disk brake mechanism

The movement of fluid in a hydraulic pipeline is considered as one dimensional and unsteady, i.e. all local speeds are considered equal to the average speed and depend on time. The pressure, also, is considered identical at all points of the cross section and depends on longitudinal coordinate of the pipeline and time. Such movement of fluid is characterized by occurrence of a wave of increased and lowered pressure, which is distributed from the place of pressure change and deformation of the pipeline walls with the velocity of sound.

Equation of the fluid continuity can be written in a differential form as follow:

$$\frac{\partial}{\partial t}[S(x)\rho] + \frac{\partial}{\partial x}[S(x)\rho v] = F_1(x), \quad (1)$$

where ρ, v are density and velocity of fluid, $S(x)$ is cross section area of the pipeline, $F_1(x)$ is discharge of fluid mass to the unit of the length, in the pipeline.

Equation of fluid flow impulse (momentum):

$$\frac{\partial}{\partial t}[S(x)\rho v] + \frac{\partial}{\partial x}[S(x)(p + \rho v^2)] + \Pi(x)\tau + S(x)\rho a_x = F_2(x) + p \frac{\partial S}{\partial x}, \quad (2)$$

where p is fluid pressure, $\Pi(x)$ is perimeter of cross section of the pipeline, τ is tangential fluid stress in the inner surface of the pipeline, a_x is acceleration along x axis, $F_2(x)$ is kinetic energy of the fluid flow in the pipeline to the unit of area.

The system of equations (1) and (2) can be written as the system second-order quasi-linear differential equations

$$[A]\left\{\frac{\partial u}{\partial t}\right\} + [B]\left\{\frac{\partial u}{\partial x}\right\} = \{f\}, \quad (3)$$

where a_{ij}, b_{ij}, f_i are matrices $[A], [B]$ and elements of vector $\{f\}$ which depend on t, x and elements u_i of vector $\{u\}$.

The differential equations of fluid movement in pipelines are solved by the method of characteristics. Other cylinders and pipelines are calculated in the same manner.

The equation of dynamic of electromagnetic valve (Fig 1) can be written as follow:

$$L \frac{di}{dt} + Ri = U, \quad (4)$$

where L, R are induction and active resistance of coil; i is current; U is voltage.

When the control signal of coil (U) arrives, electromagnetic valve closes or opens depending on the stage of braking. The equation of electromagnetic valve movement:

$$m_s \frac{d^2 X_s}{dt^2} = F_{em} - F(X_s \dot{X}_s), \quad (5)$$

where m_s is weight of piston; X_s is position of piston; $F(X_s \dot{X}_s)$ is valve's mechanical resistance force; F_{em} is force which is induced by electromagnets coil. Pressure in valve cavity:

$$\frac{dp_v}{dt} = \frac{K}{V} (Q_{input} - Q_{output}), \quad (6)$$

where K is modulus of elasticity of fluid; V is volume of valve cavity; Q_{input}, Q_{output} are input and output debits.

4. Dynamic Model of a Vehicle

For the analysis, a model for simulating of a vehicle behaviour was developed based on the three dimensional automobile model, as shown in Fig 2. In the simulation, vehicle responses such as the deceleration of the vehicle, stopping distance after braking and the tyre vertical load can be calculated, provided the automobile initial speed, the longitudinal road profile is given as inputs.

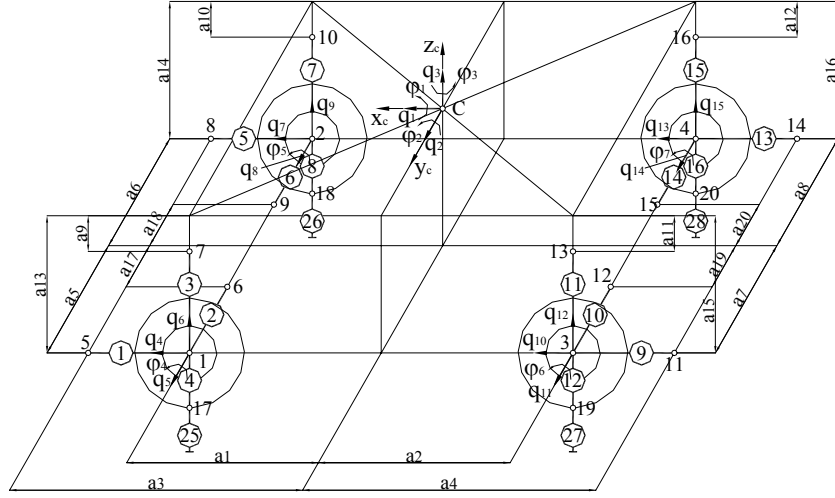


Fig 2. Three-dimensional vehicle model

The system of equations of the three dimensional model of vehicle may be presented as follows:

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{F(t, q, \dot{q})\}, \quad (7)$$

where $[M]$, $[C]$, $[K]$ are mass, damping and stiffness matrices, respectively; $\{F(t, q, \dot{q})\}$ is nonlinear load vector; $\{q\}$, $\{\dot{q}\}$, $\{\ddot{q}\}$ are displacement, velocity and acceleration vectors, respectively.

The dynamic model of the disk brake system includes the brake rotor, housing, a piston, pads, a hydraulic cylinder, a wheel and part of the suspension (Fig 3).

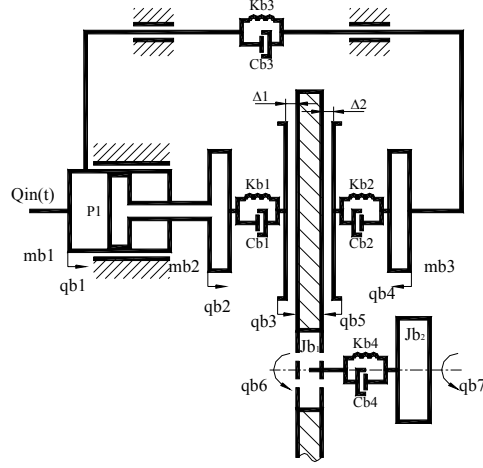


Fig 3. The main scheme of the disk brake system

The system of equations of the calliper disk brake may be presented as follows:

$$[M]\{\ddot{q}_b\} + [C]\{\dot{q}_b\} + [K]\{q_b\} = \{F(t, q_b, \dot{q}_b, p_1)\}; \quad (8)$$

$$\dot{p}_1 = \frac{K(p)}{V_0 + S(q_{b2} - q_{b1})} (Q_{in} - S(\dot{q}_{b2} - \dot{q}_{b1})); \quad (9)$$

$$M_b = R_a (F_{N1} + F_{N2}) f; \quad (10)$$

where Q_{in} is debit of fluid; S is a cross section area of the piston; V_0 is initial volume of the cylinder; M_b is a brake torque; R_a is an average radius; f is friction coefficient between pad and disk; $q_{b1}, q_{b2}, \dots, q_{b7}$ are generalized coordinates.

The tyre friction force depends on the vertical force, longitudinal tyre slip (λ), velocity (v) and wheel slip angle (α):

$$F_T = F_N \mu(\lambda, v, \alpha), \quad (11)$$

where F_N is a vertical reaction force.

When studying the dynamics of the vehicle, the intricate interaction between the wheel and the road surface, i.e. the characteristics of the tyre to even the initial stochastic road surface is taken into account. The effectiveness of the tyre evening characteristics high frequency components (harmonics) of the surface are not taken into consideration

5. Experimental Research on the Process of Vehicle Braking

An experiment was carried out for verification of the results obtained in the simulation of three dimensional vehicle with hydraulic brake system (with/without ABS) and disk brake system.

For this purpose the brake cylinder pressure measurement equipment was fitted for a synchronous operation with the VMZ 100 meter of deceleration. Following parameters were registered every 0.02 s with the VMZ 100 meter during the experiment:

- depression force of working braking pedal;
- braking deceleration of the vehicle.

For such testing 4 technically proper vehicles were selected having an average operation time of 4 years. Experimentation was carried out on horizontal asphalt-concrete road paving (dry and wet surface). Vehicles were in braking without and with the antilock brake system (ABS) with initial speed of 40, 60 and 80 km/h. The VMZ 100 meter recorded the whole process of vehicle braking to the operation memory and transmitted the data through the serial interface RS 232 into the personal computer.

For the pressure measurement two high pressure transmitters were fitted to Rover 620 vehicle hydraulic brake system (between the ABS block and front wheels braking cylinders). Transmitters have 0–10 VDC analogue output, which corresponds with the measured pressure of 0–25 MPa. For the signal registering the analogue/digital scope with two measurement channels was used. The amount of operational memory of the scope allowed us to register the pressure of two front wheels brake cylinders every 2.5 ms during whole braking process with the accuracy of 0.21 MPa.

6. Simulation and Experimental Results

During the mathematical experiment for the 3D mathematical model (Fig 2, 3) Rover 620 as a prototype was used. Hydraulic brake system of this vehicle is shown on Fig 1. During the mathematical simulations and natural experimentations the following results were achieved:

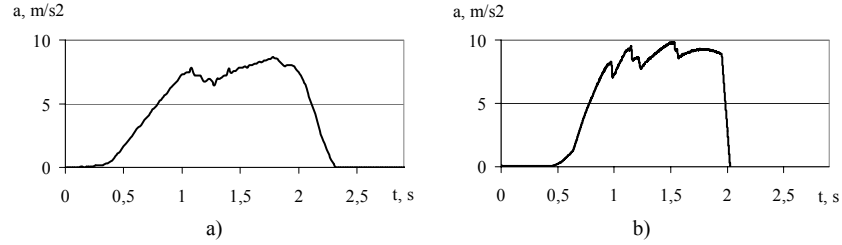


Fig 4. Alteration of vehicle deceleration a (initial speed 40 km/h, dry asphalt): a – experimental data, b – simulation results

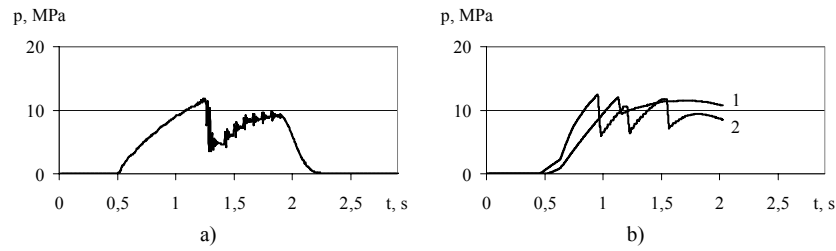


Fig 5. Alteration of vehicle brake cylinders pressure p (initial speed 40 km/h, dry asphalt): a – experimental data; b – simulation results; 1 – front wheels; 2 – rear wheels

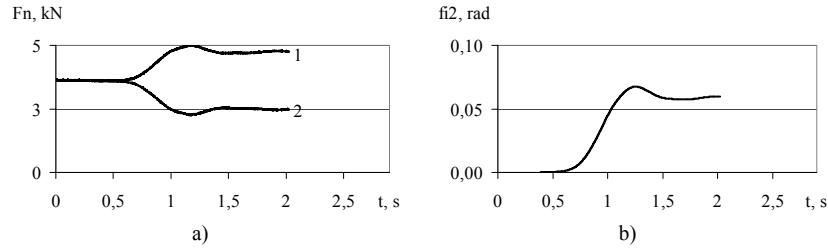


Fig 6. Alteration of normal force F_N (a) and vehicle body angle about Y (b):
1 – front wheels; 2 – rear wheels (initial speed 40 km/h, dry asphalt)

As we can see from alterations of braking process main parameters (Fig 4, 5, 6), the mathematical model shows very good resembling with the natural experimentation data.

7. Conclusions

Emergency braking of a vehicle is bound with many factors, such as the behaviour of the driver, the drive of the vehicle braking system, the braking mechanisms, the condition of the tyres, and the properties of the pavement. This process involves all parameters of the system “the driver – the vehicle – the road”. In order to investigate the efficiency of braking process upon specific conditions, it is necessary to examine all physical processes that take place in the vehicle on pressing the brake pedal.

Upon the completion of the experimental and theoretical investigation on emergency braking of vehicles, the following scientific and practical conclusions had been formulated:

1. A general mathematical model of vehicle with hydraulic braking system on its emergency braking had been developed, where dynamic, thermodynamic in solid systems and fluid hydrodynamic processes were assessed. The model enables to examine various cases of emergency braking with assessment of the driver's reaction, parameters of the vehicle' technical condition and the pavement condition.
2. On the base of the results of the mathematic simulation of the hydraulic braking system, it was found that hydrodynamic processes of the system are affected by the physical and mechanical processes of the fluid, the relative content of air in the fluid, the volumetric losses (fluid leakage) in the system, the physical and mechanical properties of the tubes, volumes of individual cavities, the masses of moving solid bodies and the forces of friction. In course of the natural and mathematical experiments, it was found that the average duration of hydrodynamic transitional processes in hydraulic braking system may be up to 0.5 s.
3. On the research on the car with hydraulic ABS on its emergency braking, the mathematical and natural experiments of the system showed that hydrodynamic processes in ABS system are considerably impacted by the controlling algorithm, the electro mechanic parameters of electromagnetic valves as well as geometrical and mechanical parameters of the slave cylinders. On testing the ABS system, pressure in the system varied on the average between 3.5 and

12.0 MPa. The frequency of pressure pulsations that directly affects the braking efficiency depends on the time of opening–closing of valves that in real systems is close to 10 ms. In the work, ABS algorithm is realized, where control is carried out according to the known dependence of the wheel/road adherence on the relative slip, i.e. opening and closing of valves is controlled dependently on the critical value of slip.

4. A mathematical model of a disk braking mechanism had been developed, where dynamic and thermodynamic processes that take place in the mechanism, the physical and mechanical properties of rubbing bodies, the geometrical parameters of the mechanism and the initial air gap between the rubbing surfaces were assessed. The mathematical experiments showed that the average duration of the transitional processes that take place in the disk braking mechanism and directly impacts the braking efficiency is to 7 ms.
5. A mathematical model of the wheel/road interaction had been developed, where physical and mechanical properties of the tyre, the micro roughness at the tyre/road contact, the tyre's ability to suppress high frequency roughness of the road, the dependence of the adherence coefficient of the specific pavement on the relative slip of the tyre, velocity of movement and the wheel slip angle had been assessed.
6. A spatial mathematical model of a car had been developed, where dynamic properties of the suspension as well as inertial properties and geometrical parameters of the car had been assessed. On simulating the emergency braking of the car, it was found that efficiency of the braking process is affected by the parameters of the suspension that cause changes of the reaction forces between the wheel and the road surface. On Rover 620 mathematical experiment, the reactions to the rear wheels decreased by 37% that caused reduction of their braking efficiency. The mathematical and natural experiments of Rover 620 vehicle on emergency braking showed that the maximum braking acceleration varies in the range between 8.10 and 9.94 m/s² for dry paving and in the range between 7.68 and 8.84 m/s² for wet paving.
7. A general mathematical model of vehicle with hydraulic braking system that's computing is realized in the system of the applied software *Compaq Visual Fortran Professional v 6.3* system had been developed. The model provides possibilities for research the hydrodynamic processes that take place in the system of braking; enables to define more closely the movement parameters of the vehicle in the emergency braking mode and may be applied for analysis of

traffic events, improvement of vehicle braking systems as well as a manual for training professionals in transport engineering.

Published works on the topic of the dissertation

In the acknowledged periodical editions

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13. Bogdevičius, M.; Vladimirov, O. Brakes as an Active Vehicle Safety System. In: Reports of 8th Conference of the Young Scientists “Lithuania without the Science – Lithuania without the Future”, held in Vilnius on 12 of May 2005. Transport. Vilnius: Technika, 2005, p. 48–52.

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LENGVOJO AUTOMOBILIO SU HIDRAULINE STABDŽIŲ SISTEMA STABDYMO PROCESO PARAMETRŲ TYRIMAS

Mokslo problemos aktualumas

Kiekvienais metais transporto priemonių kiekis Lietuvoje auga sparčiais tempais. Todėl didėja eismo įvykių tikimybė keliuose. Kelių eismo saugumo problema yra viena pagrindinių mūsų visuomenės problemų.

Eismo saugumo didinimo keliuose priemonės skirstomas į dvi stambias kategorijas: priemonės ir technologijos skirtos apsaugoti keleivius ir vairuotojus nuo galimų sužeidimų avarijos metu (pasyvi sauga); priemonės ir technologijos, kurios sukonstruotos padėti vairuotojui išvengti pačios avarijos (aktyvi sauga).

Pastaruoju laiku vis didesnis dėmesys skiriamas automobilio stabdžių sistemai, kaip vienam pagrindinių aktyvios saugos elementų. Automobilio ekstremalus stabdymas yra vienas paskutiniųjų veiksmų, kuriuo vairuotojas bando išvengti autoavarijos.

Šiame darbe nagrinėjama transporto priemonių, atskirų jos sistemų įtaka eismo saugumui, sukūrus jų matematinius modelius, kurie tiksliai aprašo fizinius procesus, vykstančius atitinkamose transporto priemonių sistemose. Matematiniai modeliai įgalina gana tiksliai ir greitai išnagrinėti šių sistemų darbo procesus ir jų įtaką transporto priemonės judėjimui. Tyrinėjant transporto priemonių dinamiką, galima gauti naudingos informacijos sprendžiant eismo saugumo problemas: kelių būklės ir atskirų transporto priemonės sistemų (stabdžių sistema, stabdžių antiblokavimo sistema (ABS), rato sąveika su kelio paviršiumi) poveikį jos judėjimui bei žmogaus saugumui.

Darbo tikslas ir uždaviniai

Darbo tikslas – išnagrinėti šiuolaikinio lengvojo automobilio su hidrauline stabdžių sistema stabdymo procesą, atliekant eismo įvykių ekspertizes ir tolimesnius hidraulinių stabdžių sistemų mokslinius tyrimus.

Tikslui pasiekti suformuluoti šie uždaviniai:

- Išanalizuoti automobilio hidraulinių stabdžių sistemas, jų pritaikymo ypatumus tiriant automobilio stabdymo dinamiką.
- Sudaryti automobilio hidraulinės stabdžių sistemos be ABS ir su ABS matematinius modelius, įvertinant hidraulinių sistemų fizines mechanines savybes ir ABS veikimo algoritmus.
- Sudaryti erdvinį lengvojo automobilio dinaminį modelį kartu su konkrečia hidrauline stabdžių sistema, diskinių stabdžių mechanizmais, įvertinant rato ir kelio sąveiką.

- Atlikti natūrinius ekstremaliai stabdomų lengvųjų automobilių su hidrauline ABS sistema bandymus, kurių metu nustatyti stabdžių skysčio slėgio pulsacijas sistemoje ir automobilio pagrindinių judėjimo parametrų reikšmes: lėtėjimo pagreičio kitimo dėsningumus, tikrąjį judėjimo greitį, faktinį automobilio stabdymo kelią.
- Atlikti lengvojo automobilio su hidrauline stabdžių sistema ekstremalaus stabdymo matematinius eksperimentus, kurių metu nustatyti:
 - a) automobilio stabdymo proceso pagrindinius parametrus: pagreitis, greitis, stabdymo kelias, santykinis slydimas, sukibimo koeficientas;
 - b) hidraulinės stabdžių sistemos darbo charakteristikas: slėgiai skirtinguose sistemos taškuose, skysčio judėjimo greičiai, pagreičiai, cilindro eigos ir kt.

Mokslinis naujumas

Sudarytas kompleksinis automobilio su diskiniiais stabdžių mechanizmais ir hidrauline stabdžių sistema bei rato sąveika su kelio paviršiumi matematinis modelis, kuriame įvertinta: slėgio bangų sklaidimas hidraulinėje sistemoje; oro kiekis skystyje; slėgio nuostoliai; skysčio sąveika su hidraulinės sistemos mechaniniais elementais (stūmokliais); skysčio klampumas; ABS sistemos reguliavimas, įvertinant sukibimo koeficiento ekstremumo reikšmes; rato sąveiką su kelio paviršiumi; automobilio pakabos elementų charakteristikos; diskinių stabdžių mechanizmų standumas; trinties koeficiento tarp trinkelio ir disko priklausomybė nuo temperatūros; trinkelio frikcinės medžiagos standumas; padangų fizinės – mechaninės savybės; sukibimo koeficiento priklausomybė nuo santykinio slydimo ir automobilio greičio.

Tyrimų metodika

Darbe pateikti eksperimentiniai ir teoriniai stabdomų lengvųjų automobilių judėjimo parametrų tyrimai. Atliekant tyrimus buvo taikomi matematinės analizės metodai. Eksperimentiniai tyrimai buvo atliekami naudojant:

- lėtėjimo pagreičio matavimo prietaisą (deselerometrą) VZM 100 su bandymo rezultatų nuskaitymo programine įranga;
- aukšto slėgio daviklius Danfoss;
- analoginį – skaitmeninį osciloskopą Hameg 1507-3 su bandymo rezultatų nuskaitymo programine įranga SP107E ir kitais priedais, reikalingais autonominiam prietaiso darbui;

Matematiniams modeliams sudaryti panaudotas matematinio programavimo paketas Maple. Originalių modelio skaičiavimo programų Fortrano kalba sukūrimui panaudotas programavimo paketas Compaq Visual Fortran.

Praktinė vertė

Sudaryti lengvojo automobilio su hidrauline stabdžių sistema modeliai duoda galimybes tirti hidrodinامينius procesus, vykstančius sistemoje stabdymo metu; leidžia tiksliau nustatyti transporto priemonės judėjimo parametrus, esant ekstremalaus stabdymo režimui; ir gali būti taikomi analizuojant eismo įvykius, bei tobulinant automobilių stabdžių sistemas.

Darbe daromos prielaidos

1. Hidraulinės stabdžių sistemos modelyje priimamos šios prielaidos:
 - Skystis yra spūdis ir klampus;
 - Skysčio judėjimo magistralėmis parametrai kinta skysčio tekėjimo išilgine kryptimi ir yra suvidurkinami pagal vamzdelio skersmenį;
 - Slėgio kitimas konkrečiose hidraulinės stabdžių sistemos talpose (cilindrai ir kt.) modeliuojamas kaip koncentruotų parametų.
2. Automobilio su diskiniiais stabdžių mechanizmais modelis sudarytas iš koncentruotų masių, sujungtų tarpusavyje tampriais, tampriai – klampiais ir frikciniais ryšiais.
3. Sukibimo su keliu koeficientas priklauso tik nuo santykinio slydimo, automobilio judėjimo greičio ir skersidės kampo.
4. Eksperimentiniai automobilių stabdymo tyrimai atlikti tiesioje lygioje nepašiuokštinto asfaltbetonio dangos kelio atkarpoje, kai pradinis judėjimo greitis 40, 60 ir 80 km/val.
5. Eksperimentinių slėgio matavimo tyrimų metu daroma prielaida, kad magistralės iki jutiklio slėgio nuostoliai yra mažesni negu matavimo paklaidos, todėl išmatuotas jutiklio slėgis lygus stabdžių cilindro slėgiui.

Ginamieji teiginiai

- Automobilio hidraulinės stabdžių sistemos modelis;
- Automobilio su diskiniiais stabdžių mechanizmais modelis;
- Hidraulinės stabdžių sistemos parametų kitimas ekstremaliojo stabdymo metu;
- Automobilio ekstremalaus stabdymo metu vykstančių dinaminų procesų parametų kitimas.

Darbo apimtis

Darbą sudaro bendra darbo charakteristika, 4 skyriai, išvados, literatūros sąrašas, publikacijų sąrašas. Bendra disertacijos apimtis – 103 puslapiai, 62 iliustracijos, 9 lentelės ir 2 priedai.

Išvados

Automobilio ekstremalus stabdymas susijęs su daugeliu faktorių: vairuotojo elgsena, automobilio stabdžių sistemos pavara, stabdžių vykdymo mechanizmai, padangų stovis ir kelio dangos charakteristikos. Šis procesas apima visus sistemos „vairuotojas – automobilis – kelias“ parametrus. Norint ištirti stabdymo proceso efektyvumą prie konkrečių sąlygų būtina išnagrinėti visus fizikinius procesus, kurie vyksta automobilyje, paspaudus stabdžių pedalą.

Atlikus eksperimentinius ir teorinius ekstremaliai stabdomų automobilių tyrimus, suformuluotos šios mokslinės ir praktinės išvados:

1. Sukurtas bendras ekstremaliai stabdomo automobilio su hidrauline stabdžių sistema matematinis modelis, kuriame įvertinti kietų kūnų sistemų dinaminiai, termodinaminiai ir skysčio hidrodinaminiai procesai. Modelis leidžia nagrinėti įvairius ekstremalaus stabdymo atvejus, įvertinant vairuotojo reakciją, automobilio techninio stovio parametrus ir kelio paviršiaus būklę.
2. Iš gautų hidraulinės stabdžių sistemos modeliavimo rezultatų nustatyta, kad sistemos hidrodinaminiai procesams įtakoja skysčio fizinės–mechaninės savybės, santykinis oro kiekis skystyje, turiniai nuostoliai sistemoje (skysčio nutekėjimai), vamzdelių fizinės–mechaninės savybės, atskirų ertmių tūriai, judančių kietų kūnų masės ir trinties jėgos. Iš natūrinio ir matematinio eksperimentų nustatyta, kad hidrodinaminių pereinamųjų procesų hidraulinėje stabdžių sistemoje vidutinė trukmė gali siekti iki 0,5 s.
3. Ekstremaliai stabdomo lengvojo automobilio su hidrauline ABS sistema tyrimų metu iš sistemos matematinio ir natūrinio eksperimentų nustatyta, kad ABS sistemos hidrodinaminiai procesams didelį reikšmingumą turi valdymo algoritmas, elektromagnetinių vožtuvų elektromechaniniai parametrai, bei darbo cilindų geometriniai ir mechaniniai rodikliai. Testuojant ABS sistemą, slėgis sistemoje vidutiniškai svyravo nuo 3,5 iki 12,0 MPa. Slėgio pulsacijų dažnis, tiesiogiai įtakojantis stabdymo efektyvumą, priklauso nuo vožtuvų atidarymo – uždarymo laiko, kuris realiose sistemose artimas 10 ms. Darbe realizuotas ABS algoritmas, kai valdymas vyksta pagal žinomą rato sukibimo su keliu priklausomybę nuo santykinio slidimo, valdant vožtuvų atidarymą – uždarymą priklausomai nuo slidimo kritinės reikšmės.
4. Sukurtas diskinių stabdžių mechanizmo matematinis modelis, kuriame įvertinti mechanizme vykstantys dinaminiai ir termodinaminiai procesai, besitrinančių kūnų fizinės–mechaninės savybės, mechanizmo geometriniai parametrai ir pradinis oro tarpelis tarp besitrinančių

- paviršių. Iš matematinių eksperimentų nustatyta, kad pereinamųjų procesų, vykstančių diskiniame stabdžių mechanizme ir tiesiogiai įtakojančių stabdymo efektyvumą, vidutinė trukmė siekia iki 7 ms.
5. Sukurtas rato ir kelio paviršiaus sąveikos matematinis modelis, kuris įvertina padangos fizinės–mechaninės savybes; kontakte tarp padangos ir kelio esančius mikronelygumus; padangos savybę slopinti aukšto dažnio kelio nelygumus; konkrečios kelio dangos sukibimo koeficiento priklausomybę nuo padangos santykinio slidimo, judėjimo greičio ir skersinės kampo.
 6. Sukurtas lengvojo automobilio erdvinis matematinis modelis, kuriame įvertintos pakabos dinaminės savybės, automobilio inercinės charakteristikos ir geometriniai parametrai. Modeliuojant automobilio ekstremalųjį stabdymą nustatyta, kad stabdymo proceso efektyvumui įtakoja pakabos parametrai, dėl kurių keičiasi reakcijos tarp rato ir kelio paviršiaus jėgos. Rover 620 matematinio eksperimento metu reakcijos į galinius ratus sumažėjo 37 %, kas nulėmė jų stabdymo efektyvumo sumažėjimą. Matematinių ir natūrinių ekstremaliai stabdomo automobilio Rover 620 eksperimentų metu nustatyta, kad maksimalus stabdymo pagreitis sausai dangai svyruoja $8,1\text{--}9,9\text{ m/s}^2$ intervale, šlapiai dangai – $7,7\text{--}8,8\text{ m/s}^2$ intervale.
 7. Sukurtas bendras automobilio su hidrauline stabdžių sistema modelis, kurio skaičiavimas realizuotas taikomosios programos *Compaq Visual Fortran Professional v 6.3* sistemoje. Modelis duoda galimybes tirti hidrodinaminį procesą, vykstančią sistemoje stabdymo metu; leidžia tiksliau nustatyti transporto priemonės judėjimo parametrus, esant ekstremalaus stabdymo režimui; ir gali būti taikomas analizuojant eismo įvykius, tobulinant automobilių stabdžių sistemas, bei kaip mokymo priemonė, ruošiant transporto inžinerijos specialistus.

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Nuo 2002 m. dirba UAB „Eltalis“ produkto vadybininku.

Padėkos

Autorius nuoširdžiai dėkoja už visokeriopą pagalbą ruošiant daktaro disertaciją, atliekant eksperimentinius tyrimus ir suteiktą galimybę naudotis matavimo įranga bei priemonėmis: prof. habil. dr. M. Bogdevičiui, dr. A. Verseckui, prof. habil. dr. R. Martavičiui, dr. S. Nagurnui, A. Balsiui.

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RESEARCH OF BRAKING PROCESS' OF TRANSPORT VEHICLE WITH HYDRAULIC BRAKE SYSTEM PARAMETERS

**Summary of doctoral dissertation
Technological Sciences, Transport Engineering (03T)**

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