371. THEORETICAL AND APPLIED BASES OF NEW GENERATION ACTIVE SAFETY SYSTEMS OF MOBILE MACHINES

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Abstract. This paper considers a new approach on creation of antiblocking and antislipping systems of mobile machines, algorithms of design of a road covering for performing virtual tests of dynamics of mobile machines, algorithm of formation of actual magnitudes of forces/moments in contact "road-wheel-car" and their derivatives, software for virtual design of dynamics of mobile machines, technique of test of antiblocking system of new generation. Results of computer-aided modeling of car movement dynamics are obtained at braking with ABS, the analysis of the basic characteristics provides information about braking distance, value of longitudinal deceleration, influence of modulator speed on efficiency of brake system.

Introduction

Traffic active safety systems (ASS) of mobile machines (cars, planes, etc.) are fundamental means of increasing stability, controllability, efficiency of braking/acceleration and other dynamic characteristics. A number of pressing questions of ASS creation are considered in works [1-8]. A new principle of ABS/ASR operation based on force principle is proposed in [2]. Algorithms of adaptive control are provided in patents [2, 3]. The method of control with an integrated control system of parameters of movement is described by properties of movement of vehicles in the patent [4]. In work [5] criteria of quality, methods and algorithms of control by movement in systems of mobile machines generally are considered. In [6] the theory of operational properties of cars and vehicles with classical type ABS in a braking mode is considered. The concept and algorithms of identification of extreme situations at movement of the mobile machine is considered in [7-10]. Algorithms of classical type ABS/ASR functioning are considered in [11, 12]. Computer modeling of new generation ASS for the first time is considered in [13, 14].

Structure of new generation active safety systems

Serial ABS and ASR are based on measurements of kinematic values and identification during each moment of time in a curve of “factor of coupling-sliding of a wheel” ($\mu - s -$ curve). Thus it is inconvenient to exclude the methodical errors caused by discrepancy at identification of $\mu - s -$ curve values of course speed of the mobile machine. In the patent [1] (1993) R. Fourounjiev and V. Kim for the first time offered a new generation ABS/ASR in which measurements of angular speeds of wheels are not required. Their functioning requires:

- sensors measuring actual forces/moments in contact “road-wheel-mobile machine” or their derivatives in longitudinal and cross-sectional directions. Actual force $F_f -$ in the further we shall name the sum of internal and external forces (longitudinal/cross-sectional), acting on a wheel at movement;
- force executive drive (the modulator of pressure, the working brake cylinder);
- controller (analog-to-digital converter, digital-to-analog converter, filters, module of formation of desirable properties of movement of operated variables, intelligent regulator);
- schemes providing normal functioning of blocks of control, the control and indication of a condition of system.

In Fig. 1 block diagram of new generation ABS/ASR is presented.

Algorithm of ASS functioning

Let's consider interaction of basic elements of system considered on Fig. 1. The principle of functioning of ABS and ASR does not differ, except that the executive mechanism in ABS is the working brake cylinder, and in ASR it is the rail of the fuel pump (a high pressure for diesel engines). Therefore we shall be limited to consideration of ABS working principle. The condition of braking/accelerating wheels of the mobile machine which are being balanced under action of actual forces/moments from the brake mechanism or the engine, road and the chassis, is supervised by gauges. The output value of the moment of the executive brake mechanism is defined by total influence from the driver and ABS/ASR, built into the brake drive. Thus actual values of forces/moments depend on efforts of influence of the driver to a pedal of a brake/gas, and from operating influences of ABS/ASR.

The information from sensors acts in the control block through the filter intended for exclusion of influence of high-frequency handicaps. On the basis of the received information $\dot{F}_{il}$ (i – index of support; l – the index of a board of the machine), an intelligent regulator according to the algorithm of functioning considered in [2, 3], forms a control signal $u(t)$ which moves on input of a force executive drive. Work of the executive mechanism is provided with an energy source. In hydraulic brake system the electric motor with high-pressure pump is usually used, while in pneumatic system - the compressor with receivers.

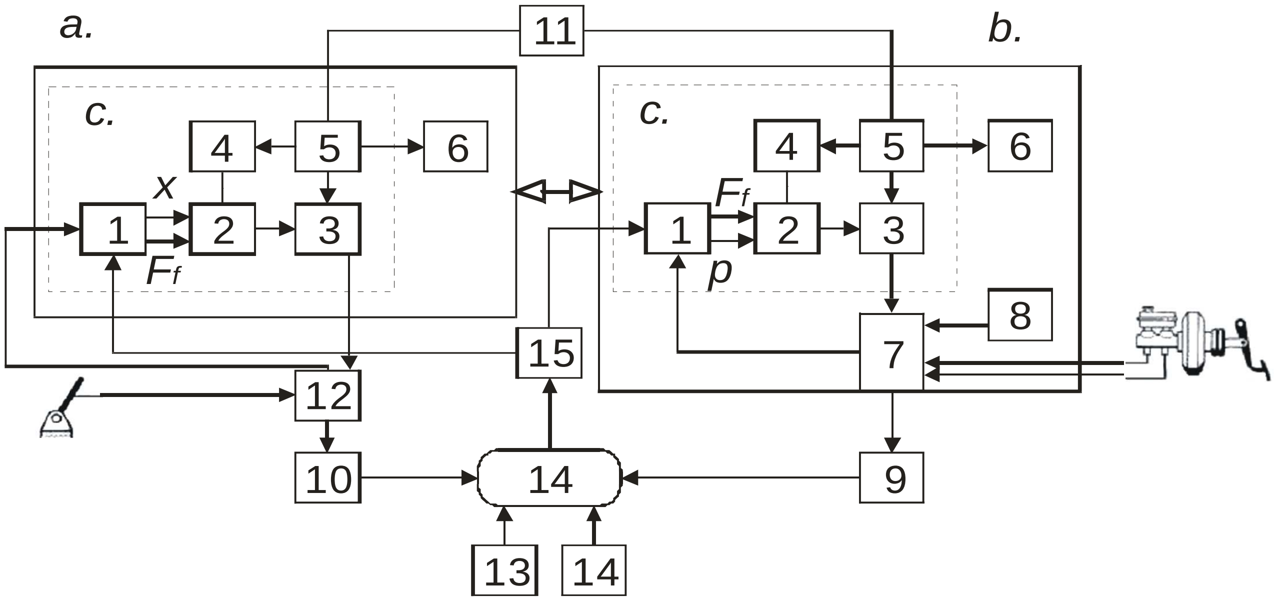


Fig. 1 – Block diagram of new generation ABS/ASR
a.) ASR; b.) ABS; c.) controller (electronic control unit (ECU));
1 – filter, 2 – intelligent regulator, 3 – power amplifier, 4 – scheme of modes stabilization, 5 – scheme of protection and control, 6 – indication of serviceability of system, 7 – pressure modulator, 8 – energy source, 9 – executive mechanism, 10 – engine, coupling, gearbox, 11 – battery; 12 – module of control of a throttle/rail of the fuel pump; 13 – external indignation; 14 – road; 15 – sensor of actually sold force/moment

At failure of the system the car brakes and accelerates in a traditional way, while the driver is informed about the failures by light and/or sound indication.

ABS that is presented in Fig. 1 functions as follows. Influence of the driver on a brake pedal is transmitted on highways to the executive brake mechanism which creates the corresponding brake moment M_{T} enclosed to a wheel of the mobile machine. Simultaneously with growth of pressure in the brake cylinder there is a decrease in angular speed of rotation of a wheel and increase of sliding of wheels. The steady range of sliding depends on a type and a condition of road covering, from type of the trunk and pressure in it, design of a protector, temperature of a road cloth and the trunk, speed of movement of the mobile machine, etc. In a steady range of sliding the derivative of actual force/moment is positive.

At approximation of actual force/moment to as much as possible sold in contact “road-wheel-mobile the machine”, the value of derivative pf actual force/moment starts to fall. At achievement of the force/moment created by a brake drive, the maximal admissible value $F_{\text{T}} = R_z\varphi$, where R_z – vertical loading on a wheel; φ – the factor of coupling in a longitudinal direction, factor of longitudinal coupling will be maximal and derivative of actual force becomes equal to zero (Fig. 2).

The controller produces an operating signal which moves on the modulator for dumping of pressure in the executive mechanism of brakes. If pressure in the brake cylinder continues to grow further, the derivative of the actual force falls below zero, and actual force in contact reduces to the value defined by vertical loading on a wheel and factor of coupling at full sliding. Thus the factor of coupling decreases to the value corresponding to full sliding of a wheel (wheels lock). Sliding of a wheel passes to an unstable range of sliding and continues to grow. The given process continues until the time of operation of the pressure modulator. Speed of modern modulators of hydraulic type makes 10-20 μs, and pneumatic type - 20-50 μs.

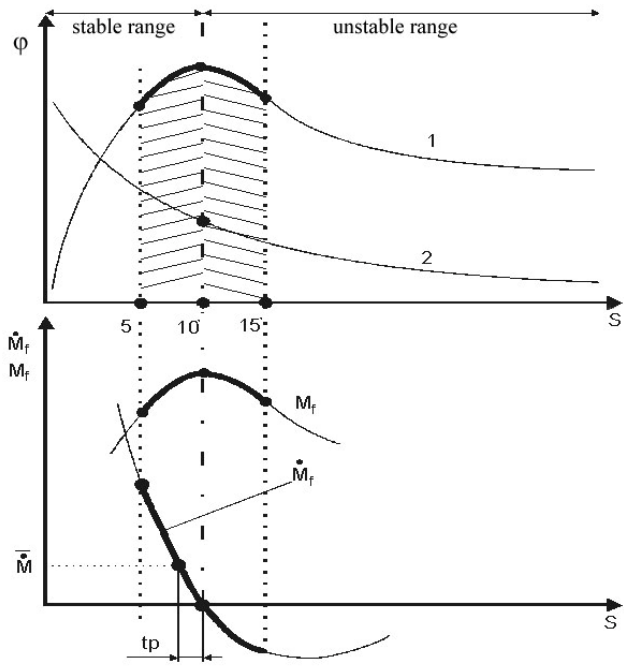


Fig. 2. Dependence of factors of longitudinal coupling of wheels from road and practically realized force/moment and its derivative from sliding a wheel
1 – factor of coupling in a longitudinal direction; 2 – factor of coupling in a cross-section direction

At operation of the modulator the valves are opened for dumping of pressure from the working cylinder. Simultaneously there is reduction of pressure by the valve of the modulator from a brake highway. Pressure in the working brake cylinder starts to be dumped from this moment. Derivative of actual force as a result decreases, reducing the most actual force accordingly. The factor of coupling starts to increase up to the maximal value, sliding of a wheel decreases and comes back in a steady range of sliding, angular speed of rotation of a wheel starts to increase. This process lasts until the derivative of actual force does not become equal to or more than zero. During this moment actual force is equal to braking force on a wheel.

At this moment, the operating signal formed by the controller, becomes equal to zero. Since this moment and time of operation of the modulator pressure in the brake cylinder continues to decrease. Actual force increases and exceeds brake force formed by a brake drive, the derivative of actual force grows. The factor of coupling continues to increase up to the maximal value, sliding of a wheel continues to decrease and comes back in a steady range of sliding, angular speed of rotation of a wheel increases.

As soon as the modulator has been operated, there is a closing of valves of dump of pressure from the working cylinder, opening of the valve of a brake highway or the valve connecting the accumulator with the brake cylinder. Since the moment when the pressure in the brake cylinder starts to increase until the derivative of actual force will not reduce to zero. During this moment of time $F_T = R_z\varphi$, factor of longitudinal coupling will be maximal, and the derivative of actual force becomes equal to zero. Sliding of a wheel will be on border of transition from a steady range of sliding to the unstable one. Angular speed of rotation of a wheel will start to fall. During this moment the controller produces an operating signal to the modulator for dumping of pressure and the cycle recurs.

The algorithm of ASR operation is similar to that of ABS except that a control signal in ASR acts on the modulator of brake pressure of driving wheels and on the mechanism of control of submission of fuel or only on the mechanism of control of submission of fuel [7, 8].

Criterion of quality of control

Criterion of quality of control at synthesis of operating functions for $k-$ target variable $x_k(t)$ ($x_k(t)-$ a derivative of actual force/moment) and its derivatives $\dot{x}_k(t),\ ...\ ,x_k^{(n-1)}(t)$ of operated system are formulated on quality of transient as integrated, and is represented as follows:

$$J_n = \int_{t_0}^{t_1} \left[\varepsilon_k{}^2 + \tau_1{}^2 \dot{\varepsilon}_k{}^2 + ... + \tau_n{}^2 \varepsilon_k{}^{(n)2} \right] dt, \qquad (1)$$

Where $\varepsilon_k(t) = \overline{x}_k(t) - x_k(t) -$ control error, $\overline{x}_k(t) -$ command value.

Desirable properties of movement of operated variables in a linear variant are set by the differential equations:

$$x_k{}^{(n)} + \beta_{n-1} x_k{}^{(n-1)} + ... + \beta_1 \dot{x}_k + \beta_0 x_k = \beta_0 \overline{x}_k, \quad (2)$$

Factors $\beta_0,...,\beta_{n-1}$ are defined through constants $\tau_1,...,\tau_n$, entering in criterion (1).

The general formulation of a problem

The condition of ASS $k-$ module of mobile machine is characterized by a target variable $x_k(t)$ and its derivatives $\dot{x}_k(t),..., x_k^{(n-1)}(t)$.

Initial and boundary conditions are set in the form of:

$$t = t_0 : x(t_0) = x_0,\ \dot{x}(t_0) = \dot{x}_0,\ ...,\ x^{(n-1)}(t_0) = x_0{}^{(n-1)}, \quad (3)$$

$$t \to \infty : x_k(t) \to \overline{x}_k,\ \ x_k{}^{(\nu)}(t) \to 0,\ \ \nu = 1,\ 2,\ ...,\ n-1. \ (4)$$

Here $\overline{x}(t) -$ command value of a target variable. Target variables can have. The condition (3) reflects an initial condition, and a condition (4) - the requirement of asymptotic stability in conformity with Lyapunov's second law. In expressions (3) and (4) for simplicity the index k is lowered.

The command value of a target variable can vary arbitrarily. So, for example, if in ABS (or ASR) as a target variable it is observed a derivative actually sold in contact the pneumatic with road of the moment $\dot{M}_{\mu}$, as command value $\bar{x}$ is accepted small positive value and brake pressure (and-or the submitted quantity of fuel in case of ASR) is regulated so that $\dot{M}_{\mu} \to \bar{x}$. Thus sliding is to the left of a maximum on $\mu - s -$ curve, however, very close to a maximum on a steady part of a curve.

Generally desirable properties of movement for all modules of the integrated system of active safety are set for the corresponding coordinates considered as days off, the differential equations:

$$\ddot{x}_k = f_k(\bar{x}_k, \dot{x}_k, x_k, t),\ k = 1, ..., m\ , \qquad (5)$$

$$t \geq 0:\ \dot{x}_k(t_0) = \dot{x}_{0k},\ x_k(t_0) = x_{0k}\ ,$$

Where $f_k(.)-$ the set operators, generally nonlinear. Boundary conditions correspond to (3) and (4). Restrictions and functions of preference $\mu_k(k = 1, ..., m_{\mu})$ for indistinctly certain functions and the parameters making information base of system are set also.

It is required to construct the regulators $u_k(.),\ k = 1, ..., m$ providing desirable properties of movement (5) during each moment of time at satisfaction of restrictions and regional conditions (3) and (4) for each module of system.

The formulation of a problem also includes control of linear and nonlinear systems by linear and nonlinear criteria at the precise and indistinct task of desirable properties of movement and information base of system. Thus, all the problems solved by modules of integrated system of active safety, are formulated in the uniform form. Therefore creation of a control system becomes essentially simpler and more economical. Thus for each module it is required to concretize only target variables $x_k(t)$ and their command values $\bar{x}_k$.

Modeling of actual forces/moments

During computer-aided modeling and computer-aided design of the mobile machine ASS it is necessary to model type and properties of a covering under various wheels of the mobile machine and systems arising in contact “road-wheel-mobile the machine”, actual forces/moments and/or their derivatives. When modeling dynamics of the mobile machine we used the nonlinear spatial mathematical model of movement providing an opportunity of the task of various types of a road covering for wheels of various boards, for example type «mixt» or various combinations of types, alternating them both on boards, and from one board, and also an opportunity of a variation of factors of coupling for various types of coverings.

For computer-aided modeling we have developed the virtual range including the module “Road Site Editor” (subsequently called "Editor"). In the editor the surface of the rectangular form in the value $l \times h$ of meters, where $l-$length, and $h-$the width of a road site consisting of square cells of the any value a, with various type of a road covering is formed. In the program module basic types of road covering are possible: dry/wet asphalt, dry/wet soil road, sand, rolled/unrolled snow, ice, etc.

For each type of road covering it is necessary to set color of a covering which appearance will be displayed at designing range, the maximal value of factors of longitudinal and cross-sectional coupling and their value at full sliding wheels.

After creation of a road covering it can be kept in a binary file on any data carrier that allows, having created type of a covering once to use it in any other software which supports a format of the file. The kept type of a covering can be edited: for any type of a covering it is possible to change factors of coupling in longitudinal and cross-sectional directions, factor of resistance of environment and to change color. The kept road covering is used in the program module of ASS virtual design of mobile machines.

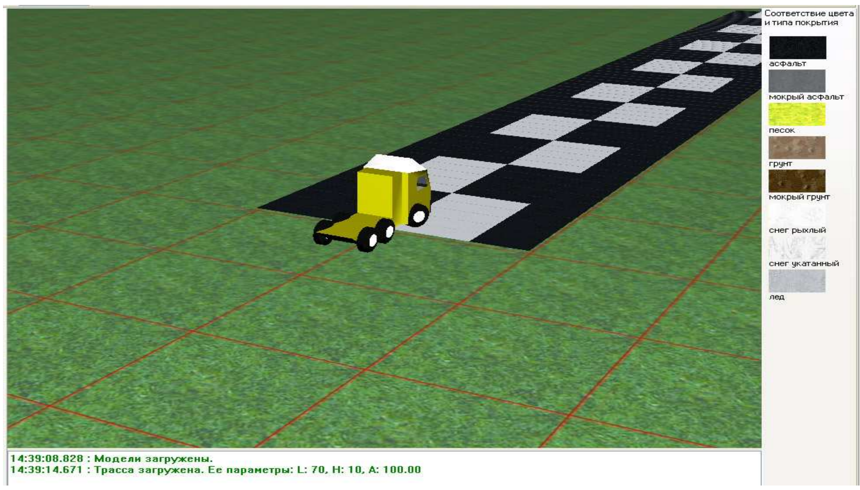


Fig. 3. Interface of 3D visualization

In Fig. 3 present form of 3-dimensional visualization of dynamics of the mobile machine movement with use of the covering designed in "Editor".

At computer-aided modeling of dynamics of mobile machine with new generation ASS the original algorithm of formation of actual forces/moments and/or their derivative wheels in contact to a basic surface is used. The analysis of work [6] has enabled determination of the tendency of change of actual force and its derivative system in contact “road-wheel-mobile machine” to various situations.

Let's consider transients for actual brake forces and their derivatives at modeling of movement of the mobile machine without ABS/ASR in a mode of dispersal and emergency braking. The given process consists of 2 phases.

The first phase starts during the moment of the beginning of braking/acceleration and proceeds till the moment of time when brake/traction force become more than as much as possible sold force on a wheel, it is the moment that corresponds to transition of sliding of a wheel from a steady range in unstable, thus the factor of coupling in a longitudinal direction passes through extremum of $\mu - s -$ curve.

The second phase begins after transition of sliding of the trunk in an unstable range of sliding and comes to an end at a full stop of the mobile machine or when the traction moment on a wheel becomes less than as much as possible sold moment in contact “road-wheel”.

Performed research work has demonstrated that actual contact of wheels processes can be approximated by the decision of the differential equation of the first order:

$$\dot{x} + 2atx = 0$$
$$t \geq t_0 : x(t_0) = x_0$$

Where x_0 – the value of a variable $x(t)$ corresponding to the approach of "extreme event", $a = a(t_{pp}, \varphi_x)$ – the parameter identified on experimental data, t_{pp} – time of transient of change of actual force for particular type of a road covering, $\varphi_x(t)$ – current value of factor of coupling in a longitudinal direction.

The decision of this equation looks like:

$$x(t) = x_0 e^{-at^2}$$

It is easy to see, that process $x(t)$ sharply decreases with growth t.

The differential equation with the right part is generally considered:

$$\dot{x} + 2atx = 2at\overline{x}\ , \qquad (6)$$
$$t \geq t_0 : x(t_0) = x_0\ ,$$

Where $\overline{x}$ – the set "command" value.

We shall present the equation (6) in the form of:

$$\dot{x} = 2at(\overline{x} - x)\ . \qquad (7)$$

The decision of the equation (7) is a function:

$$x(t) = x_0 + \overline{x}(1 - e^{-at^2})\ .$$

In fig. 4 the graphic decision (7) is presented at $\overline{x} = 1$, $a = 1$, $x_0 = 0$.

Using (8), change of factual forces/moments $F_f(t)$, their derivatives $\dot{F}_f(t)$, and also factor of coupling $\varphi_x(t)$ for biphase process can be described by the following algorithm:

$$\begin{cases} \left.\begin{array}{l} F_f(t_i) = F_t(t_i), \\ \dot{F}_f(t_i) = \dot{F}_t(t_i) \\ \varphi_x(t_i) = \varphi_{xmax}(1 - \dfrac{F_f(t_i)}{\varphi_{xmax} R_z}) \end{array}\right\}, \text{ if } F_t(t) \leq \varphi_{xmax} R_z \\ \left.\begin{array}{l} F_f(t_i) = R_z \varphi_{xmax} - R_z(\varphi_{xmax} - \varphi_{xmin}) e^{-at_i^2} \\ \dot{F}_f(t_i) = 0 - \dot{F}_{max} a t_i e^{-at_i^2} \\ \varphi_x(t_i) = \varphi_{xmax} - (\varphi_{xmax} - \varphi_{xmin})(1 - e^{-at_i^2}) \\ i = \overline{0..n} \end{array}\right\}, \text{ if } F_t(t) \geq \varphi_{xmax} R_z \end{cases} \qquad (9)$$

Where $F_t(t)$ – brake/traction force/moment on a wheel, $R_z(t)$ – normal reaction to a wheel, φ_{max} – the maximal value of longitudinal/cross-sectional factor of coupling (on a curve “factor of coupling-sliding of a wheel”), φ_{min} – the maximal value of longitudinal factor of coupling at full sliding of wheel for current type of a road covering; t_i – time considered from the moment of approach of "extreme event" that started after excess by brake/traction force of as much as possible sold force/moment for the certain type of a road covering, $i = \overline{0..n}$, $\dot{F}_{max} = \dot{F}_{max}(\varphi_x)$ – the parameter identified on experimental data, depending on factor of coupling of a road covering.

In Fig. 5 results of computer-aided modeling of forces are provided: actual brake, formed on a wheel brake drive, and also their derivative systems in contact “road-wheel-mobile the machine” for a road covering of type asphalt at finishing a wheel before full blocking.

Let's consider change of actual brake forces and their derivatives at modeling movement of the mobile machine with ABS/ASR in a mode of dispersal and braking. The given process consists of 4 phases. The second, third and fourth phases repeat.

The first phase begins during the moment of the beginning of braking/dispersal and proceeds till the moment of time when brake/traction forces become more than as much as possible sold force on a wheel that corresponds to transition $\dot{F}_f$ through zero (in negative area of values).

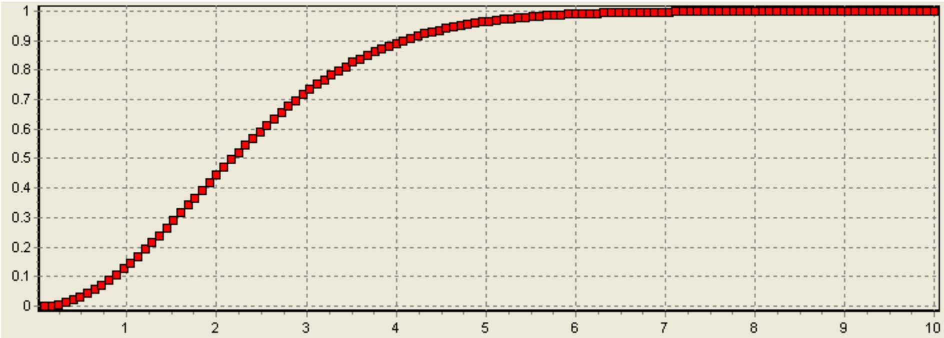


Fig. 4. Decision of the equation (6)

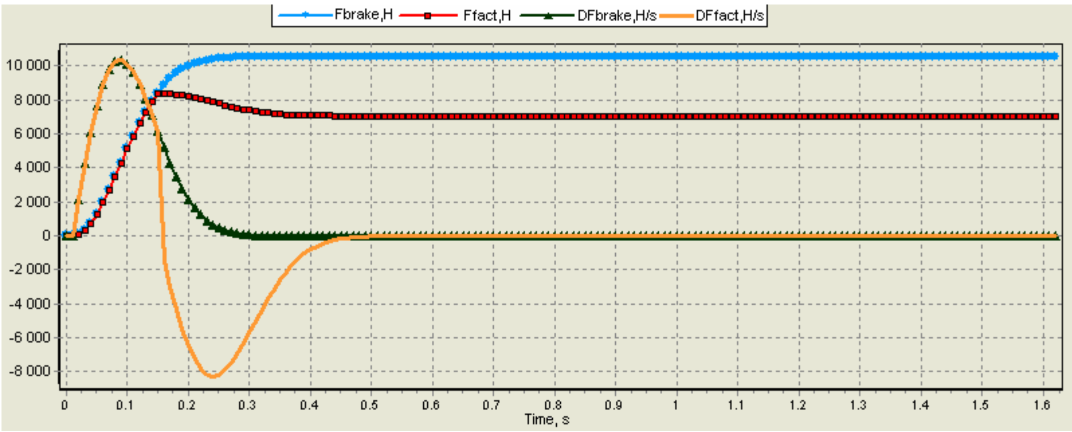


Fig. 5. Results of computer-aided modeling of actual forces and their derivatives
In contact of system "road-wheel-mobile the machine"

The second phase begins during the moment of time when there is an excess by brake/traction forces of as much as possible sold force on a wheel, and comes to an end, when the executive mechanism will work after submission of an operating signal on dump of pressure in a mode of braking or at dispersal when the operating signal will reduce submission of fuel and-or will lift pressure in the brake cylinder.

The third phase begins during the moment of time when there is an operation of the executive mechanism after submission of an operating signal on dump of pressure in a mode of braking or at dispersal when the operating signal will reduce submission of fuel and-or will lift pressure in the brake cylinder and comes to an end before the executive mechanism will start to function after reception of an operating signal in a mode of braking - on increase in pressure, in a mode of dispersal - on increase in submission of fuel and-or dump of pressure in the brake cylinder up to zero.

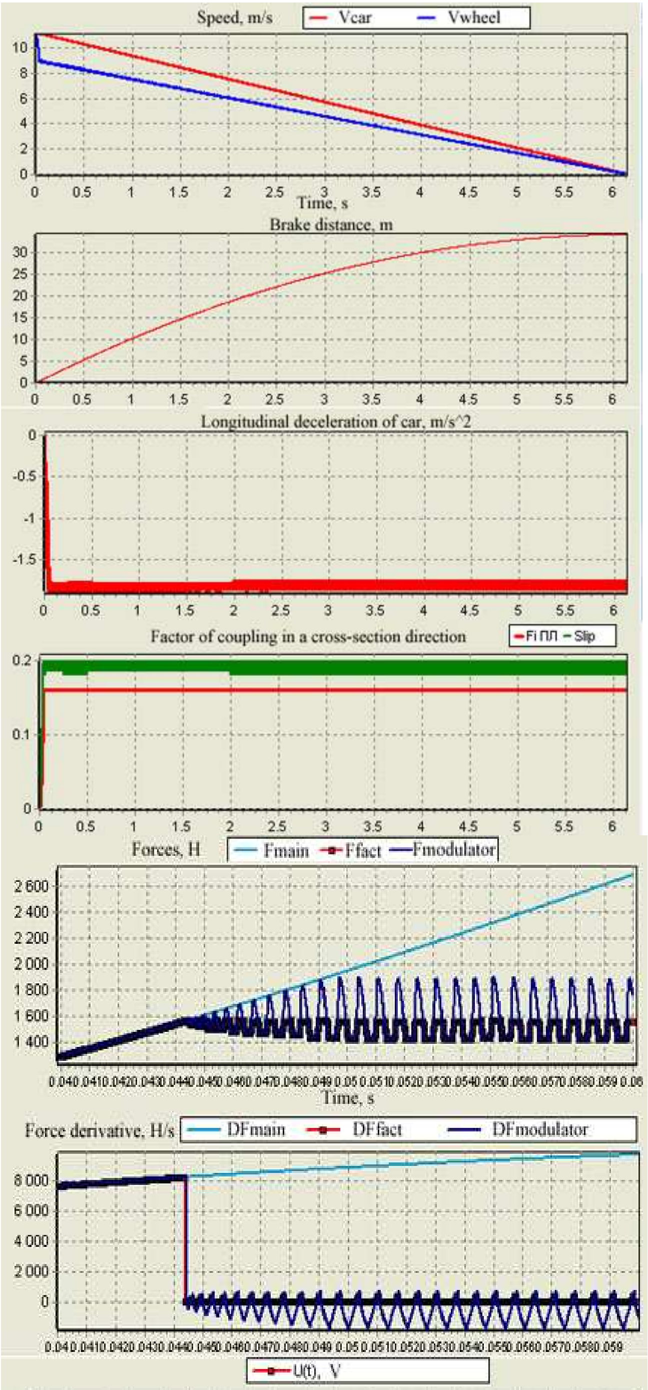
The fourth phase begins after operation of the executive mechanism after submission of an operating signal on increase of pressure in a mode of braking or at dispersal when submission of fuel will increase and/or pressure in the brake cylinder will start to be dumped up to zero. The fourth phase will last till the moment of time while brake/traction forces do not become more than as much as possible sold force on a wheel. There will be further a cyclic change of a phase 2, 3 and 4 until the driver will not reduce pressure upon a pedal "brake/gas" or there will be no change of a road covering to smaller factor of coupling on greater.

Thus, the algorithm described above can be presented in the form of:

$$
\begin{cases}
\left.\begin{aligned}
&F_f(t_i)=F_t(t_i),\\
&\dot{F}_f(t_i)=\dot{F}_t(t_i),\\
&\varphi_x(t_i)=\varphi_{xmax}\Big(1-\frac{F_f(t_i)}{\varphi_{xmax}R_z}\Big)
\end{aligned}\right\}, \mathit{if}\ F_t(t)\le\varphi_{x\max}R_z\ \&\ \dot{F}_t(t)\ge 0;\\
\left.\begin{aligned}
&F_f(t_i)=R_z\varphi_{xmax}-R_z(\varphi_{xmax}-\varphi_{xmin})e^{-at_i^2},\\
&\dot{F}_f(t_i)=0-\dot{F}_{max}at_ie^{-at_i^2},\\
&\varphi_x(t_i)=\varphi_{xmax}-(\varphi_{xmax}-\varphi_{xmin})(1-e^{-at_i^2}),
\end{aligned}\right\}, \mathit{if}\ F_t(t)\ge\varphi_{xmax}R_z\\
\left.\begin{aligned}
&F_f(t_i)=F_t(t_i),\\
&\dot{F}_f(t_i)=\dot{F}_t(t_i),\\
&\varphi_x(t_i)=\varphi_{xmax}\Big(1-\frac{F_f(t_i)}{\varphi_{xmax}R_z}\Big),
\end{aligned}\right\}, \mathit{if}\ F_t(t)\le\varphi_{xmax}R_z\ \&\ \dot{F}_t(t)\le 0;\\
i=\overline{0..n}.
\end{cases}
$$

Results of computer-aided modeling

Results of computer-aided modeling of brake dynamics of the car with ABS are presented in Fig. 6 and 7. Apparently, at increase in speed of the modulator by 2 times the brake way makes 33,55 m and is reduced to 3,6 % due to more effective work of system in the field of an extremum of $\mu - s -$curve, the established deceleration has decreased by 0,05 m/s^2. Maintenance of longitudinal factor of coupling in a range of 19-20 % of sliding of a wheel, and also higher average value of cross-sectional factor of coupling is provided.



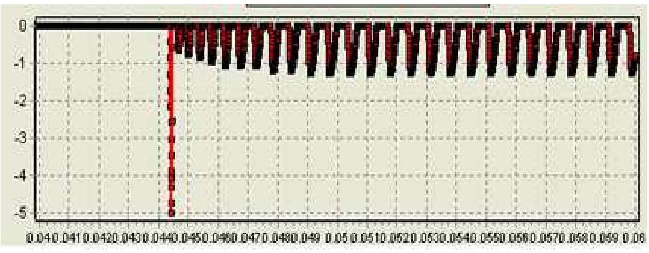


Fig. 6. Transients at braking the mobile machine with ABS. Speed of the two-position modulator $t_M = 50$ ms

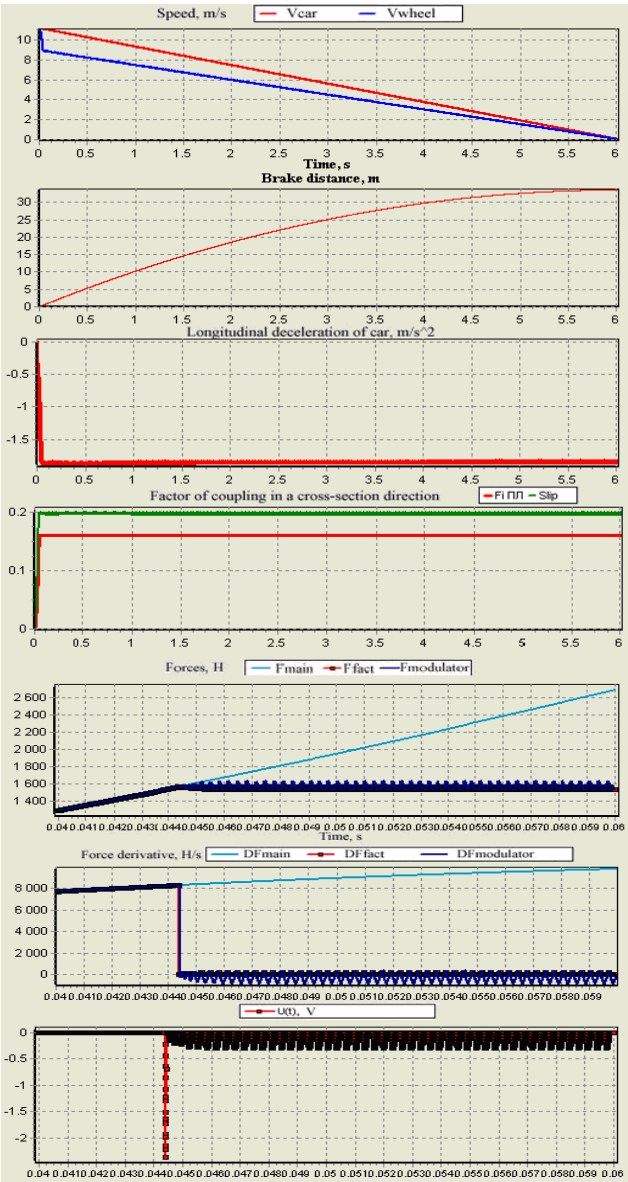


Fig. 7. Transients at braking the mobile machine with ABS. Speed of the two-position modulator $t_M = 25$ ms

Conclusion

Paper reports on computer-aided modeling of the mobile machines dynamics equipped with ABS and ASR. Modeling with use of new algorithms of the adaptive control, combining high accuracy and speed without repeated regulation owing to work on nonlinear criteria of quality of control is provided. Besides, simplicity of the task of any desirable properties of movement of operated variables ABS/ASR is obtained. Stability of movement of operated system is ensured. Implemented intelligent regulators enable realization of limiting opportunities of used executive drives.

The new principle of functioning of ABS/ASR is based on measurements of forces/moments that allows to use derivatives of higher orders in regulators, that increase quality of control and reduces influence of high-frequency handicaps. So, for example, the derivative of force corresponds to the third derivative of angular moving of wheels.

Proposed computer-aided modeling has demonstrated efficiency of the new concept, methods and algorithms of adaptive control. The factor of sliding of a wheel was in a zone of a maximum of factor of coupling in a longitudinal direction and concerning high values of factor of coupling in a cross-sectional direction.

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