Разработан усовершенствованный профиль железнодорожного колеса с контргребнем, что обеспечивает дополнительный контакт в горизонтальной плоскости при поперечных колебаниях колесной пары относительно рельсового пути, добавляет экипажу устойчивости и увеличивает силы сопротивления колес против схода с рельсов при прохождении криволинейных участков пути, а также при упругом отклонении рельсов в результате силового взаимодействия.

Научная новизна. Получила дальнейшее развитие методика создания рабочего профиля колес для специального подвижного состава, которая учитывает контргребень на поверхности качения. Впервые получены закономерности силового взаимодействия колесной пары с колесами с контргребнем и боковой грани головки рельса. Впервые получена зависимость, характеризующая влияние поперечных сил при вписывании экипажа в кривые при контакте колеса с контргребнем с рельсом.

Практическая значимость. Разработана колесная пара для подвижного состава горнорудного и шахтного транспорта, профиль которой характеризуется наличием дополнительной дорожки качения и контргребень, что обеспечивает противодействие схода колесной пары с рельсов в то время, когда основной гребень колеса вкатывается на рабочую поверхность рельса или имеет место распор пути в результате упругой деформации рельсов. Предложенная конструкция колесной пары защищена патентами Украины на полезную модель.

Ключевые слова: *колесная пара, контргребень, сход с рельсов, гребень колеса, рельсовый путь*

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EFFECT OF ANTILOCK BRAKE SYSTEM ON BASIC PARAMETERS OF TRANSPORT VEHICLE TRANSMISSION

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ВПЛИВ АНТИБЛОКУВАЛЬНОЇ СИСТЕМИ НА ОСНОВНІ ПАРАМЕТРИ ТРАНСМІСІЇ ТРАНСПОРТНОГО ЗАСОБУ

Purpose. The objective of the paper is to study antilock brake systems (ABS) effect upon the basic parameters of hydrostatic mechanical transmission (HMT) in the process of emergency braking.

Methodology. The research has involved current methods of solving differential equations of mathematical model of transport vehicle braking process as well as the comparing methods to analyze braking process involving ABS and emergency braking at the expense of braking system in terms of kinematic disconnection of engine from a driving wheel with HMT of various schematic designs.

Findings. As a result of the complex theoretical research, the effect of ABS upon operating pressure differential within hydrostatic drive, angular velocity of hydraulic pump shaft, range of values of angular velocity and driving and driven clutch shafts, braking efficiency of a transport vehicle, and transport vehicle deviation from the specified trajectory have been determined.

Originality. It is the first time when quantitative assessment of ABS effect upon HMT kinematic and power parameters has been performed; it allows increasing technical level of transmissions even at the wheeled vehicle design stage at the expense of timely considering of possible overload occurring while operating in the process of ABS braking.

Practical value. The proposed methods and applied mathematical models have made it possible to develop the approach to determine and take into account possible HMT overloads arising in terms of wheel transport vehicle with ABS braking even within the design period.

Keywords: *hydrostatic and mechanical transmission, transmission, wheel transport vehicle, braking process, controllability, braking efficiency*

Introduction. ABS system is widely used both in passenger and lorry motor transport, however its iteration into tractor is quite a complex task as running characteristics of lorry and passenger motor transport differ considerably from tractor ones because of different sizes of wheels of front and rare axes of the latter and giant tire sizes.

Equipping of wheeled tractors with ABS results in braking efficiency increase, both stability and controllability improvement, growth in average motion velocity as well as traffic safety increase.

To compare with mechanical transmissions, wheel tractors with HMT have additional facility of service braking: transfer of the control member of HMT hydraulic unit (joystick) into the position corresponding to zero velocity of tractor movement ensures slow decrease of a vehicle motion until its complete stop. However, currently the problem of ABS and HMT interaction has not been researched yet. ABS effect upon the change of HMT kinematic and power parameters has not been studied at all.

Analysis of the recent research and unsolved aspects of the problem. Efforts to improve ABS as one of the most efficient means to increase safety of self-propelled vehicles have been carried out within many decades; though even modern ABSs leave much to be desired. Papers [1, 2] concern both experimental and theoretical studies of braking process of transportation means equipped with various ABSs, the development of algorithms of their functioning as well as the structure of both separate ABS components and the whole system.

It is known [3] that the feature of ABS developed by "Knorr-Bremse" company for Fendt 900 tractors is as follows: owing to high inertia of tractor wheels, if conditions to lock any wheel emergence, then ABS control unit sends signal to brake release not only for corresponding pressure modulator; it also connects with the system of tractor control which can steer the wheel effecting on it through Vario gear if modulator cannot perform its functions independently. Both front wheels are controlled together even if there are different surfaces under each wheel; rare wheels are controlled separately.

Currently ABS samples have been also developed for all Case IH Puma tractors irrespective of transmission and maximum velocity. If stepless transmission and maximum tractor velocity of 60 km/h are available, then ABS is series configuration; it is optional for other transmission variants. The developed "Case IH" ABS systems is based on the components also used for Iveco lorries belonging to the same corporate group. The system runs on compressed air. Converter transforms pneumatic signals into impulses for hydraulic braking system the tractor is equipped with.

Despite the fact that HMTs have been widely used for process and technological, forestry engineering, construction and road machines, for wheel and crawler tractors as well as for mine diesel locomotives [4–6], information concerning ABS effect upon the changes in HMT kinematic and power parameters is not available in scientific sources.

Presentation of the main research. It is impossible to solve the problems concerning studies of braking process without application of adequate mathematical model. To develop generalized mathematical spatial multimass nonlinear model of wheeled tractor braking process, the newest tractor with Fendt 936 Vario stepless HMT (one of the most powerful tractor of "Fendt" company) was selected as the prototype. The model is performed in the form of separate units; it involves five groups of equations: description of the internal combustion engine characteristics and equation of crankshaft movement; description of operating processes within HMT; mathematical description of wheels and bearing surface interaction; mathematical description of braking system; description of the movement of both unsprung and spring masses taking into account the effect of suspension and tire stiffness [7].

The spatial model [7] was used as the basis of studying ABS effect on changes in kinematic parameters and power parameters of prospective tractor HMTdesigns.

Unfortunately, there is no free access to the data concerning the way of pressure modulation in ABS; structure of pressure modulators is unknown either. The sources [2, 8] show that pulse-width modulation belonging to the ways with controlled pressure fluctuation is the optimal one from the viewpoint of regulation quality and adaptive properties. It was taken as the basis while describing ABS operating processes; prospective pressure modulator was taken as the actuating element [8].

Conditions of generating pulsating signal of rectangle pulse-width modulation while modeling braking process are as follows

$$C_{ij} = C_0 + K_h \cdot \int_0^t \left(\dot{\omega}_{ij} - \frac{K_{nij} \cdot \ddot{X}}{r_{dij}} \right) dt, \qquad (1)$$

where C_0 is constant value of duty ratio corresponding to maximum pressure in braking drive; K_h is sensitivity coefficient; $\dot{\omega}_{ij}$ is angular wheel deceleration ($i = r$ is the right side, $i = l$ is the left side, $j = 1$ is the front axle, $j = 2$ is the rare axle); K_{nij} is coefficient of trial actions, $K_{nij} > (1 - S^*_{ij})$; S^*_{ij} is relative skidding corresponding to maximum coefficient of adhesion; $\ddot{X}$ is longitudinal deceleration of a self-propelled vehicle; r_{dij} is dynamic radius of a wheel; t is deceleration time.

If $\dot{\omega}_{ij} > 0,$ then

$$C_{ij} = \text{const}. \qquad (2)$$

If $\omega_{ij} = 0,\ \ddot{X} \neq 0,$ then duty ratio is determined from the expression

$$C_{ij} = -K_c \cdot t + C'_{0ij}, \qquad (3)$$

where K_c is constant coefficient setting the rate of pressure decrease in case of complete wheels locking; C'_{oij} is the value of C_{ij} at the moment of switching to condition (3) from (1) or (2).

Insufficient K_{nij} value can decrease the efficiency of trial action resulting in decrease of braking efficiency due to slow setting for $\ddot{X} = \ddot{X}_{\max}$; in turn, excessive value will result in considerable wheel overbraking. K_h value is used to determine sensitivity of the system to varying wheel dynamic state. In terms of minor K_h values ABS reaction to dynamic change state will be slow; in case of excessive value of this coefficient it is possible to observe decreased stability of regulation process due to overregulation as a result of increased reaction of the system to dynamic state change [2].

Increase in braking efficiency, controllability and stability of a self-propelled machine with pneumatic braking drive and ABS with pulse-width modulation is possible at the expense of improvement of conditions to generate pulsating signal: value of K_{nij} trial action and K_h sensitivity coefficients should be changeable and depend upon traffic conditions and wheels load. Paper [9] concerns this very problem; the paper proposes to determine the value of K_h sensitivity coefficient from the following expression

$$K_h = \frac{1}{-0.1653 \cdot \ddot{X}^2 - 0.4808 \cdot \ddot{X} + 20.6929}. \quad (4)$$

The value of K_{nij} trial action coefficient is determined from the expression

$$K_{nij} = K_{n0} - a \cdot S_{ij} + b \cdot \ddot{X}, \quad (5)$$

where K_{n0} is the initial value of trial action coefficient at the moment of braking beginning; a, b are constant coefficients being determined according to the methodology described in paper [2].

Expressions (1–5) were used to explain ABS operating processes of a tractor with HMT.

According to the result of complex static analysis of HMT, two prospective tractor designs have been obtained: the first one is with input differential (Fig. 1–2, maximum coefficient of efficiency is 0.823) and the second one with output differential (Fig. 3–4, maximum coefficient of efficiency is 0.883). Both HMT schemes were designed so that maximum velocity being implemented within traction range in terms of motion resistance coefficient being 0.5 would be 10 km/h.

These are the schemes shown in Fig. 1–4 which were the basis to determine ABS effect on changes in kinematic parameters and power parameters of HMT. Studies were carried out in terms of emergency braking of wheel tractors in terms of kinematic engine tearway from driving wheels. Emergency braking has been considered as it helps keeping probability of ABS switching on.

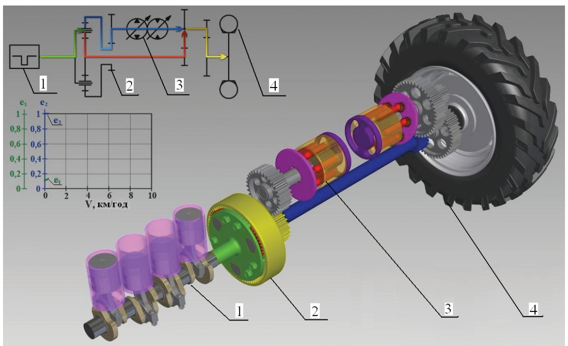

Fig. 1. 3-D HMT image with input differential and transmission links specified with power motion directions (tractor motion velocity is 0.1 km/h):

1 is internal combustion engine; 2 is planetary gear set; 3 is HD; 4 is a wheel

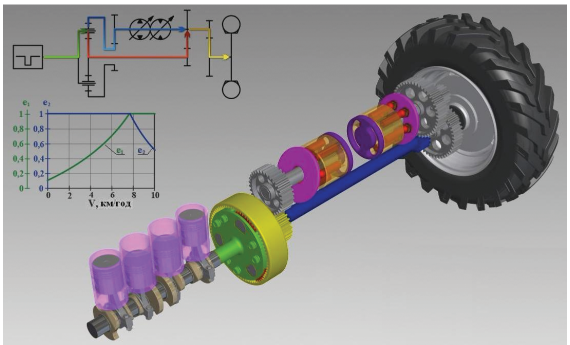

Fig. 2. 3-D HMT image with input differential and transmission links specified with power motion directions (tractor motion velocity is 10 km/h)

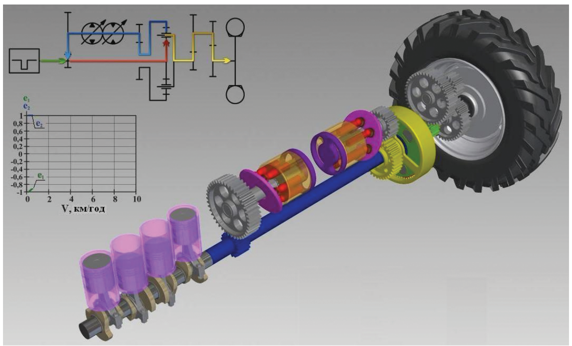

Fig. 3. 3-D HMT image with output differential and transmission links specified with power motion directions (tractor motion velocity is 0.1 km/h)

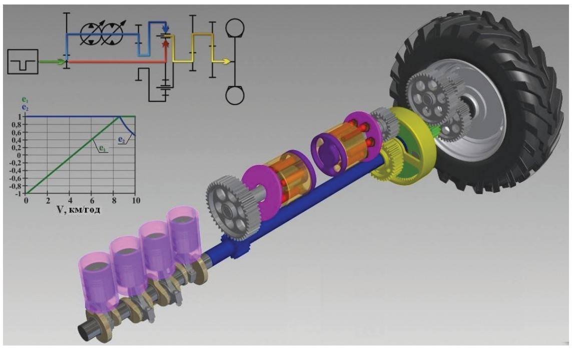

Fig. 4. 3-D HMT image with output differential and transmission links specified with power motion directions (tractor motion velocity is 10 km/h)

Motion velocity of modern tractors with HMT is 60 km/h; that is why additional range is introduced into HMT prospective designs; supplementary range is transportation, switching to which allows implementing maximum velocity of 60 km/h when motion resistance coefficient is $f = 0.05$.

Let us analyze dynamics of braking process of a tractor according two HMT plans from Fig. 1–4 within the road with dry asphalt and snow in terms of curvilinear motion and operation within transportation range (driving back axle, braking at the velocity of 60 km/h, tractor movement with ballast of 6 t mass, motion resistance coefficient is 0.05) with the use of mathematical model and approaches given in paper [10].

The nature of motion of wheel tractors is interesting as while braking at velocity as a rule, starting from 15 km/h, not only jump-like changes in working liquid pressure within HD is observed. Sharp increase in values of angular velocities of HMT links followed by overloading of both HD and planetary gear set and a clutch is also available. Moreover, curvilinear motion modeling makes it possible to analyze both braking efficiency and controllability of tractors.

The table lists results of theoretical studies. Fig. 5 shows one of the graphic dependences demonstrating pulsing changes in HMT parameters.

Symbols in the Table and Fig. 5 include: V is velocity of a tractor; ΔP is working pressure difference within HD; e_1 and e_2 are parameters to control HD; angular velocity of a shaft of hydraulic pump ω_1, hydraulic motor shaft ω_2, satellite gears ω_s; difference between values of angular velocities of a drive clutch shaft and driven clutch shaft $\Delta\omega$; t is braking period; S_g is braking distance; Δmax is maximum deviation from the guided path.

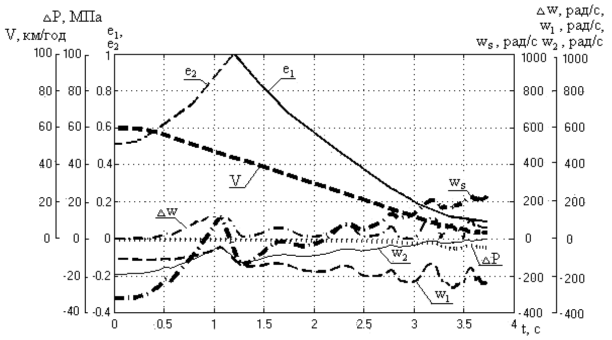

Fig. 5 Results of braking modeling with ABS (HMT scheme with input differential)

Analysis of the results testifies that if braking process involves ABS (when values of parameters experience change then HMD control corresponds to changes of real velocity of motion of a tractor automatically) increase in braking efficiency up to 0.43 % , working pressure difference within HMD up to 26.74 %, angular velocity of a shaft of hydraulic pump up to 10.0 %, decrease in deviation from guided path down to 64.13 %, difference between values of drive clutch shaft and driven clutch shaft down to 59.32 % are observed in comparison with emergency braking at the expense of brak-

Table

The results of analysis concerning braking process of wheel tractors

t, s	S_g, m	Δ_{max}, m	$\lvert\Delta P\rvert_{max}$, MPa	$\lvert\omega_1\rvert_{max}$, rad/s	$\lvert\omega_2\rvert_{max}$, rad/s	$\lvert\omega_s\rvert_{max}$, rad/s	$\lvert\Delta\omega\rvert_{max}$, rad/s
HMD with input differential							
Braking process with ABS							
Road surface is dry asphalt							
3.70	32.64	0.55	4.74	276.10	190.80	324.60	119.00
Road surface is snow							
8.60	72.63	0.94	4.60	221.90	190.80	324.60	118.00
Braking process without ABS							
Road surface is dry asphalt							
3.65	32.65	1.24	3.74	276.10	190.80	324.60	110.00
Road surface is snow							
8.61	72.94	2.61	3.67	207.00	190.80	324.60	111.00
HMD with output differential							
Braking process with ABS							
Road surface is dry asphalt							
3.66	32.35	0.55	1.19	154.00	130.40	331.40	108.70
Road surface is snow							
8.51	71.03	0.99	1.19	142.30	130.40	331.40	116.30
Braking process without ABS							
Road surface is dry asphalt							
3.63	32.36	1.25	1.19	140.00	130.40	331.40	74.00
Road surface is snow							
8.49	71.10	2.76	1.19	140.90	130.40	331.40	73.00

ing system in the context of kinematic tearway of engine from drive wheels.

Conclusions and recommendations for further research. The paper has innovatively performed quantitative evaluation of ABS effect on kinematic parameters and power parameters of HMD; that makes it possible to improve technical level of transmissions even at the design stage. That can be done at the expense of preliminary consideration of overloading being a result of ABS use during braking process.

It has been determined that use of ABS in the context of wheel tractors with HMD provides improvement of their braking efficiency, i.e. braking distance shortening; improvement of trajectory controllability, i.e. decrease in deviation from guided path as well as load decrease in terms of transmission components if values of changes in parameters of HMD control correspond to changes in real velocity of motion of a tractor automatically.

Results of the research may be recommended to be used by enterprises engaged in the design and manufacturing of HMDs as well as organizations whose activities are connected with operation of wheel tractors with HMDs.

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Мета. Дослідження впливу антиблокувальної системи (АБС) на основні параметри гідрооб'ємно-механічної трансмісії (ГОМТ) у процесі екстреного гальмування транспортного засобу.

Методика. При проведенні дослідження використані сучасні методи рішення диференціальних рівнянь математичної моделі процесу гальмування транспортного засобу, а також методи порівнянь для аналізу процесу гальмування з АБС та екстреного гальмування за рахунок гальмівної системи при кінематичному від'єднанні двигуна від ведучих коліс транспортного засобу з ГОМТ різноманітного схемного виконання.

Результати. У результаті проведеного комплексу теоретичних досліджень встановлено вплив АБС на перепад робочого тиску в гідрооб'ємній передачі, кутову швидкість валу гідронасоса, розбіжність між значеннями кутових швидкостей ведучого й веденого валів зчеплення, гальмівну ефективність транспортного засобу, відхилення транспортного засобу від заданої траєкторії.

Наукова новизна. Уперше виконано кількісну оцінку впливу АБС на кінематичні й силові параметри ГОМТ, що надає можливість ще на стадії проектування колісних транспортних засобів підвищити технічний рівень трансмісій за рахунок завчасного врахування можливого перенавантаження, яке виникає при використанні у процесі гальмування АБС.

Практична значимість. На основі запропонованих методів і використаних математичних моделей розроблено підхід, що дає змогу на стадії проектування визначати й урахувати можливі перенавантаження ГОМТ, які виникають при гальмуванні колісних тракторів з АБС.

Ключові слова: *гідрооб'ємно-механічна трансмісія, транспортний засіб, процес гальмування, керованість, гальмівна ефективність*

Цель. Исследование влияния антиблокировочной системы (АБС) на основные параметры гидрообъемно-механической трансмиссии (ГОМТ) в процессе экстренного торможения транспортного средства.

Методика. При проведении исследования использованы современные методы решения дифференциальных уравнений математической модели процесса торможения транспортного средства, а также методы сравнений для анализа процесса торможения с АБС и экстренного торможения за счет только тормозной системы при кинематическом отсоединении двигателя от ведущих колес транспортного средства с ГОМТ разнообразного схемного исполнения.

Результаты. В результате проведенного комплекса теоретических исследований установлено влияние АБС на перепад рабочего давления в гидрообъемной передаче, угловую скорость вала гидронасоса, расхождение между значениями угловых скоростей ведущего и ведомого валов сцепления, тормозную эффективность транспортного средства, отклонение транспортного средства от заданной траектории.

Научная новизна. Впервые выполнена количественная оценка влияния АБС на кинематические и силовые параметры ГОМТ, что позволяет еще на стадии проектирования колесного транспортного средства повысить технический уровень трансмиссий за счет заблаговременного учета возможной перегрузки, которая возникает при использовании в процессе торможения АБС.

Практическая значимость. На основе предложенных методов и использованных математических моделей разработан подход, позволяющий на стадии проектирования определять и учитывать возможные перегрузки ГОМТ, возникающие при торможении колесных транспортных средств с АБС.

Ключевые слова: *гидрообъемно-механическая трансмиссия, транспортное средство, процесс торможения, управляемость, тормозная эффективность*

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