IMPACT OF PARAMETERS OF POWER TRANSMISSION SYSTEM STATE ON VEHICLE'S WORKING LIFE AND POWER EFFICIENCY

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Abstract: *This paper deals with a change of states of power transmission system elements up to the achievement of boundary conditions based on a material fatigue. Depending on the level of change in states of elements, an estimation of a remaining working life of a power transmission system was given. Additionally, an estimation of a change of conditions of power transmission system elements , as well as the impact of states of elements on a power efficiency of a vehicle are presented . Besides an analytical consideration, the simulation models were created and the results of simulations presented.*

Keywords: WORKING LIFE, POWER TRANSMISSION SYSTEM, POWER EFFICIENCY, FATIGUE, SIMULATION

1. Introduction

The calculation of a working life of elements and power transmission systems in vehicles are the most often considered in reference literature starting from its state, before use, not taking into account the changes of states of elements during exploitation.

However, the changes emerge during the exploitation of the power transmission system influencing their working life on the basis of a material fatigue.

Thence the consideration of the change of states of elements and systems and impact of these changes on their working life, i.e. time of operation from the given initial state to the achievement of the working life is interesting here.

During the operation of apower transmission system in a vehicle, a mechanical, thermal, chemical and other loads act upon individual elements and on a system as a unity. Deformations, breakdowns, fatigues as well as destructions of individual elements occur under the influence of these loads leading to the changes of the basic parameters of states and parameters of functioning of the system. Additionally, it causes changes of physical and mechanical characteristics such as decrease of strength, resistance area, resistance to wearing etc.

Some of these processes such as deformations, wearing and corrosion emerge on the surfaces of elements, while the processes of weakening of materials occur inside these elements.

A particular importance for the remaining working life is related to the processes of weakening and processes of wearing.

Also, vehicle power transmission systems are complex functional and constructive systems which have to sustain a load exerted by both engine and surface.

The structural overview of a vehicle power transmission system can be seen on Fig. 1, [1].

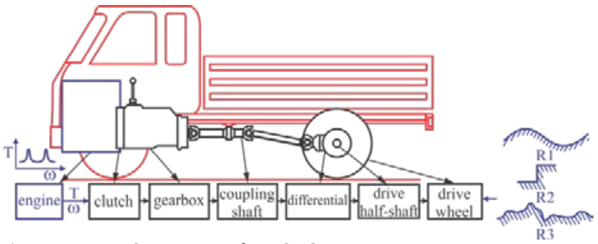


Fig. 1 *Structural overview of a vehicle power transmission system; R1- surface (general case), R2- stair-step obstacle, R3- random shape surface irregularities, [1].*

These loads create the resulting load with two main components: quasi-static and dynamic one.

During the operation of a power transmission system, all the above-mentioned loads are permanently present.

The basic types of stresses of materials leading to the changes of the states of elements in a power transmission system are the exceeding of a static strength, fatigue and wearing.

A fatigue destruction is a long-lasting process that most often begins in so-called weak zones in material. This process can, as the time elapses, be divided in the phase of occurrence of an initial fatigue crevices, phase of widening of the fatigue crevices and a phase of final destruction. Awareness of a fatigue process characteristics, namely a speed of expansion of fatigue crevices can help to foresee a time of an occurrence of failure, therefore, it can be concluded that a fatigue characterises the state of a mechanical part and can be used as a diagnostic parameter.

From the standpoint of the change in state of elements, friction and wearing of coupled surfaces of elements have a particular importance. Therefore, this type of changes of state (destruction) also characterises a technical state of the coupled elements and can be used as a diagnostic parameter.

Note that the state of elements of a power transmission system in vehicles changes during the exploitation due to wearing (dilapidation) of contact surfaces of coupled elements and deformation of elements.

A wearing is a process of a gradual change of sizes and shapes of the coupled elements, when during their mutual motion a phenomenon of friction between their surfaces occurs. A state and shape of frictional surfaces, speed of motion, loads of coupled elements as well as a range of other factors, significantly influence the process of wearing. An occurrence of clearance (play) in coupled elements representing a non-linearity with a zone of senselessness and linear parts.

A change of parameters of states of elements on the basis of clearance is considered below, and the estimation of remaining working life, as well as the impact of the state of elements on an vehicle's power efficiency are given.

Additionally, an analytical consideration of the remaining working life, simulation model and the results of simulation are also give.

2. Achievement of a boundary state on the basis of a material fatigue

In the analysis of the achievement of boundary state on the basis of material fatigue, a remaining working life of elements of power transmission system in vehicles from any determined state to the occurrence of a boundary state is considered.

The boundary state of elements of mechanical power transmission system in vehicles is mainly related to their boundary wearing.

The basic indicators of the wearing process are:

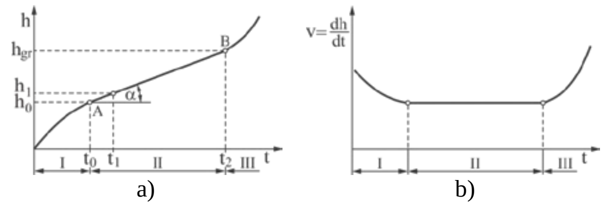
- Change of a size of elements (volume of wearing) in the process perpendicular to the friction surface – linear wearing h, Fig. 2a,
- Change of speed of wearing v=dh/dt, Fig. 2b.

There are three periods in the process of wearing: I - period of breaking-in, II - period of normal operation and III - period of breakdown wearing.

Dependence of wearing on an operation time of element, in a general case, is given by the following equation, [2,3]:

$$h = h_0 + c \cdot t^{\beta} \qquad (1)$$

The value of h_0 characterises a wearing of an element on the completion of elaborating of the system, point 1 on Fig. 2. The coefficient β represents a deterministic value determined by a structural solution of contact surfaces of the coupled elements in the conditions of their work.



a) b)

Fig. 2 *The wearing process [2,4]; a) change of size of wearing in time, b) change of wearing speed in time*

The boundary wearing according to the criterion of a flow of wearing curve is characterised by a critical point (point B on 2) dividing an area of an established and catastrophic wearing. For the elements having coatings resistant to wearing, or reinforcement with a chemical and thermal processing, the boundary wearing is determined by a thickness of a reinforced layer (finish).

A rise of load of elements, as well as a significant reduction of their working life up to the achievement of a boundary state, namely the loses of operative ability, occurs due to wearing of elements of power transmission systems in vehicles. The reduction of a working life is bigger if a vehicle is longer exploited in transitional modes.

Besides the technical criteria, a boundary state of the power transmission system in vehicles is also determined by economic criteria that are based on a minimising of specific costs.

3. Remaining working life

The remaining work life of the power transmission systems in vehicles represents a time of its operation from the given initial state to the achievement of the boundary state, when its further usage is unallowable, or not appropriate an assessment of the state as well as an estimation of the remaining work life of the transmission system are given according to technical and economic criteria.

With the ultimate wearing values defined, according to technical criteria ($h_{gr.T}$) and economic criteria ($h_{gr.E}$), the valid value is the lower one:

$$h_{gr} = \min(h_{gr.T}, h_{gr.E}) \qquad (2)$$

Ultimate wearing value according to economic criteria ($h_{gr.E}$), in most of the cases, is close to the value of allowed wearing specified by the manufacturers of transmission elements.

Residual lifetime of transmission elements, from the moment t_1, which corresponds to wearing h_1 until the moment t_2, which corresponds to maximum allowed wearing h_{gr}, may be determined in the following manner.

Through wearing curve linearisation, in the part correlating to normal wearing, Fig. 2a, we get the approximately constant wearing speed which can be expressed as [3]:

$$v_H = \frac{h_{gr} - h_1}{t_2 - t_1} = tg(\alpha) \qquad (3)$$

Residual lifetime of the element T_p is:

$$T_p = t_2 - t_1 = \frac{h_{gr} - h_1}{v_H} \qquad (4)$$

Total lifetime of the element, until reaching maximum allowed wearing, including warm-up time is:

$$T = t_0 + \frac{h_{gr} - h_0}{v_H} \qquad (5)$$

If h_{gr} is replaced with h_{doz} in the equations (4) and (5), a remaining work life of elements of the power transmission system in vehicles to the achievement of an allowable wearing is obtained.

The remaining, as well as the total working life of the power transmission system can be expressed by a traversed distance.

4. Impact of the state of a power transmission system on energy efficiency

As it has been mentioned, an occurrence of clearance is an indicator of the state of a power transmission system.

A clearance rises due to wearing, while a working ability of a vehicle, namely its working efficiency and energy efficacy decrease. The changes of its working efficiency and energy efficacies are techno – economic indicators of the change of the state of a vehicle, [5].

This impact can be illustrated by the following example.

Due to the presence of clearance in aligned link of a drive shaft a critical number of rotation of half-shaft decreases. The real value of the critical number of a drive half-shaft rotations n'_{kr} is less than the calculated value n_{kr} due to an insufficient strength a support, insufficient balance of a shaft and inaccuracy of the aligned joints. Given the abovementioned, a proper corrective coefficient K which, for a new drive half-shaft, is K=0,9÷0,95 is introduced. Having in mind this coefficient, a real value of the critical number of rotations of the drive half-shaft is:

$$n'_{kr} = K \cdot n_{kr} \qquad (6)$$

Depending on the wearing of joints of shaft, the coefficient K decreases, Fig. 3, [5,6].

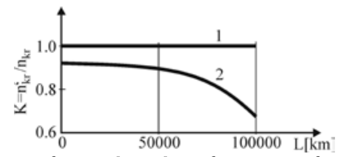


Fig. 3 *The change of critical number of rotations of a drive half-shaft, [5,6]*

5. Model of power transmission system and the results of the simulation

The system for a power transmission in vehicles, for the presence of a change of state in joints of elements (play – clearance) represents a complex elasto-intertial non-linear system with a torsional loading.

The total clearance in the system for power transmission in vehicles is divided into several places of kinematic chain, in cogged pairs, couplers, articular drive half-shafts and other joints of elements. A clearance in the power transmission system rises during the exploitation of a vehicle due to wearing. By the rise of clearance, each movement, change of speed and braking of the elements of the power transmission, especially when there is no its previous loading, cause impact stresses in the elements of the system for power transmission by an increase of clearance. For the presence of clearance, the dynamics of loadings fairly rise and these can achieve the values that several times exceed the static loadings from resistance forces.

An impact of clearance on the dynamic loading of elements of the system for power transmission in the conditions of occurrence of impulse loadings is particularly expressed.

The impact of clearance and material fatigue reduces the reliability and work life of the power transmission elements.

For the purposes of determination of a loading of the power transmission elements, with the presence of clearance in some connection of elements, it is necessary to set a mathematical model of a torque oscillation of the power transmission as a non-linear system.

Depending on the simplification degree, the power transmission can be represented with a model having two or more masses, with one or more non-linearity elements like a senselessness zone representing a clearance.

An analytical determination of a loading of power transmission elements in a non-linear model for several masses and non-linearity is very complicated. Thence a computer simulation is applied in these cases.

In cases of presence of clearance in joints of elements in individual phases of movement, a breakage of a kinematic chain occurs, followed by collision of masses yielding additional loads.

The basic task for the determination of dynamic loadings of the power transmission system elements is the creation of a mathematical model of a dynamic behaviour of the power transmission system.

However, an elasto-inertial torque model with two masses can be used for studying of a dynamic behaviour of power transmission systems. This mode enables a finding of the solution in a closed shape that is particularly convenient for the analysis of the solution. Additionally, the quality of the solution is of an acceptable level.

For the model with two masses, the reduction of mass is executed in front of and behind a reference elastic connection for which a value of loading is searched for. Additionally, the first mass is taken as a driving, while the second mass is the driven one. There is an elastic connection between these masses.

In general case, model of damped torsional oscillations of power transmission from n rotation masses can be written in the form of matrix equation, [1,5]:

$$\mathbf{J} \cdot \left\{\ddot{\varphi}\right\} + \mathbf{B} \cdot \left\{\dot{\varphi}\right\} + \mathbf{C} \cdot \left\{\varphi\right\} = \left\{\mathrm{M}\right\} \qquad (7)$$

where:
J, **B**, **C** are the matrices of inertia, damping and rigidity (nxn dimensions),
$\left\{\ddot{\varphi}\right\}, \left\{\dot{\varphi}\right\}, \left\{\varphi\right\}$ are the vectors of an angular acceleration, angular speed and angular positions of the centres of rotation masses (nx1 dimensions)
$\left\{T\right\}$ is the vector of external exciting torques, originating from the engine and motion resistance (nx1 dimensions).

The solution of matrix equation (7) with multiple masses is analytically very complex, and therefore simplified models are used [7].

So, elasto-inertial torsion models with two masses can be used as well.

General elasto-inertial torsion model with two masses is shown below on Fig. 4, [5].

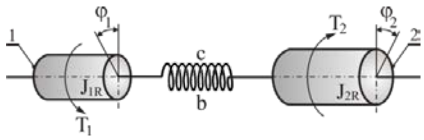


Fig. 4 *Elasto-inertial torsion model with two masses.*

The symbols on Fig. 4 have the following meanings: 1- mass of the drive part of the system, 2-driven mass, J_1- reduced inertia torque of the masses of the drive part of the system, J_2- reduced inertia torque of the masses of the driven part of the system, T_1- drive torque, T_2- load torque which may be either constant or variable (depending on the system position, time or speed), b- damping, c- reduced rigidity of the elastic system parts, φ_1- angular position of the centre of the rotational mass of the drive part of the system, φ_2- angular position of the centre of the rotational mass of the driven part of the system.

Differential equations of motion of this system in the warm-up phase are, [1,5]:

$$\begin{aligned} &J_{1R} \cdot \ddot{\varphi}_1 + b\left(\dot{\varphi}_1 - \dot{\varphi}_2\right) + c\left(\varphi_1 - \varphi_2\right) = T_1 \\ &J_{2R} \cdot \ddot{\varphi}_2 - b\left(\dot{\varphi}_1 - \dot{\varphi}_2\right) - c\left(\varphi_1 - \varphi_2\right) = -T_2 \end{aligned} \qquad (8)$$

The detailed analytical description of the elasto-inertial model with two masses and clearance is given in reference literature [5], Fig. 5.

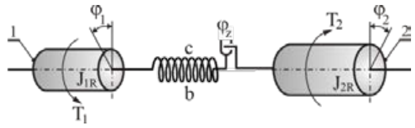


Fig. 5 *Elasto-inertial torsion model with two masses and clearance [1,5].*

The signs at Fig. 5 have the same meaning as the signs at Fig. 4, while φ_z is clearance.

The equation describing a motion of masses of the system presented at figure 5 is, [1,5]:

$$\begin{aligned} &J_{1R} \cdot \ddot{\varphi}_1 + b\left(\dot{\varphi}_1 - \dot{\varphi}_2\right) + T_C = T_1 \\ &J_{2R} \cdot \ddot{\varphi}_2 - b\left(\dot{\varphi}_1 - \dot{\varphi}_2\right) - T_C = -T_2 \end{aligned} \qquad (9)$$

Where is the torsion torque in the elastic connection with clearance is:

$$T_C = \begin{cases} c \cdot \left(\varphi_1 - \varphi_2 - \dfrac{\varphi_z}{2}\right), & \dfrac{\varphi_z}{2} \le \varphi_1 - \varphi_2 \\ 0, & -\dfrac{\varphi_z}{2} \le \varphi_1 - \varphi_2 \le \dfrac{\varphi_z}{2} \\ c \cdot \left(\varphi_1 - \varphi_2 + \dfrac{\varphi_z}{2}\right), & \varphi_1 - \varphi_2 \le -\dfrac{\varphi_z}{2} \end{cases} \qquad (10)$$

The equations (9) represent the basis for the simulation of the dynamic behaviour of the system, shown in Fig. 6.

Results of simulation

For the elasto-inertial model shown on Figure 6, we have adopted the following parameters: T_1=5150 [N·m], J_{1R}=2.66 [kg·m^2], J_{2R}=82.78 [kg·m^2], c=4329 [N·m], φ_z=0.698 [rad], [5,8,9], and T_2=100 [N·m], we performed the simulation of the movement of masses through the clearance using MATLAB-Simulink.

On Fig. 6, we gave the curves representing the torsion torque changes in the elastic connection with the clearance - curves 1 and

2, and without the clearance - curve 3, together with the torsion torque change M_1. It is necessary to point out that we have considered an ideal case where there are no other disturbances in the system.

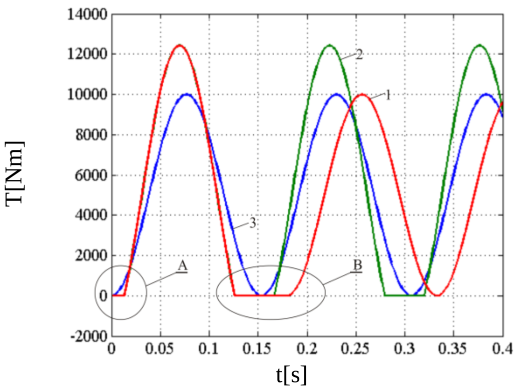


Fig. 6 *The torsion torque changes in the elastic connection; 1- the curve obtained on the basis of the model of movement of masses through the clearance in five phases (in phase three the condition b is met); A and B phases merger, 2- the curve obtained on the basis of the simplified model where the clearance has been included through the initial conditions (when there is no a dumping of clearance value in an elastic connection); 3- the curve represents the case when in the model no clearance is present, [5,8].*

Based on diagram at figure 6, the following can be concluded, [5]:

- Maximal value of a bending moment in an elastic connection with a clearance ($\varphi_z=40^0=0.698$ [rad]) – curve 1 is for 24.2 % bigger than in the case without a clearance – curve 3,
- Maximal values of a bending moment in an elastic connection with a clearance obtained by the use a model of mass motion through a clearance in five phases (curve 1) and a simplified model where a clearance is included through the initial conditions (curve 2) are the same,
- Amplitudes of curves 2 and 3 do not change with time; for curve 1, after the first amplitude of the maximal value, an oscillation with a constant amplitude whose value corresponds to the curve 3 occurs.

6. Conclusion

A friction and wearing between surfaces of coupled elements of power transmission system in vehicles have a particular importance for the change of states of power transmission elements in vehicles.

An achievement of a boundary state on the basis of a material fatigue in vehicles is related to a boundary wearing of coupled elements.

Due to a change of states of power transmission elements in vehicles, a rise of dynamic loads of elements, as well as decrease of a work efficiency and energy efficacy occur.

Also, the change of state of elements of power transmission system in vehicles decreases their remaining work live.

Based on a known state and speed of change of state of elements, a remaining work life of the power transmission system on the basis of the achievement of a maximal allowable wearing can be determined.

Based on an analytical consideration and a simulation model, it was found out that the change of state of power transmission system elements in vehicles in transitional modes multiply exceed static loadings.

7. Literature

1. Damjanović M., Popović V., Simović S., *Fluctuation of the dynamic load nature in the power transmission train,* Tehnički vjesnik – Technical gazette, Vol. 23, No.3, Slavonski Brod, 2016.
2. Jovičić S., *Osnovi pouzdanosti mašinskih konstrukcija,* Naučna knjiga, Beograd, 1990.
3. Гриневич Г.П. и др., *Надежность строителъных машин, Стройиздат,* Москва, 1983.
4. Durković R., *Prenosnici snage,* Mašinski fakultet, Podgorica, 2015.
5. Damjanović M., *Procjena preostalog radnog vijeka sistema za prenos snage teretnih vozila (Estimation of the residual lifetime of truck power transmission system).* Doktorska disertacija, Univerzitet u Bogradu, Mašinski fakultet, Beograd, 2013.
6. Бухарин Н.А., Прозоров В.С., Щукин М.М., *Автомобили*, Машиностроение, Ленинград, 1973.
7. Lukin P., Gasparyants G., Rodionov V., *Automobile chassis*, Design and calculations, First published 1989, Revised from the 1984 Russian edition, English translation, Mir publishers, Moskva, 1989.
8. Damjanović M., Durković R., *Impact of clearance to the load of elements of transmission of motor vehicles,* XXII International Automotive Conference Science and Motor Vehicles 2009, JUMV 2009, University of Belgrade, Faculty of Mechanical Engineering, Belgrade, 2009.
9. Цитович И.С., Каноник И.В., Вавуло В.А., *Трансмиссии автомобилей*, Наука и техника, Минск, 1979.
10. Damjanović M., Simović S, Durković R., *Impact of clearance to the load of elements of transmission of motor vehicles*, XXII International Automotive Conference Science and Motor Vehicles 2013, JUMV 2013, University of Belgrade, Faculty of Mechanical Engineering, Belgrade, 2013.