ANALYSIS OF CONSTRAINTS OF THE HIGH SPEED TRACKED VEHICLE IN A TURNING MODE

Victor Derzhanskii, IgorTaratorkin

Institute of Engineering Science, Russian Academy of Sciences, Russia

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This article has analyzed the dynamic processes of tracked vehicle movement in a turning mode and stated the limits of vehicle mobility in such modes. It has defined the possibility in principle to decrease the effect of constraints and to implement potential high speed qualities of the vehicle while improving the dynamic features of the steering gear system by means of synthesis of Integra-differential compensating devices.

In work [1] devoted to studying the dynamics of driving high-speed tracked vehicles (HTV) it is established that high-speed qualities on roads with intensive trajectory curvature change are in many respects constrained by power-to-weight ratio and turning moment value created by the pump-controlled hydraulic steering drive (PHSD). To increase dynamic qualities of vehicles the turning moment should be sufficient for overcoming driving resistance to turning and HTV inertial component. Otherwise, nonlinear characteristic effect of pump-controlled hydraulic steering drive of the steering gear system (SGS) caused by pressure limitation or driving fluid flow switching occurs. In these conditions it is not only dynamic stability that fails to be provided but static one as well.

However, the results of the experimental research of the controlled motion dynamics of the vehicle with high power-to-weight ratio and turning moment (angular acceleration when turning on firm ground is 1.1 radian/sec^2) show that while driving over damp concrete and swardy ground the average speed along a test snakelike route with intensive change of a trajectory curvature (half wavelength of sinusoid guiding line ΔS = 20 … 30) is much lower than the estimated one in terms of steering power conditions. Implementation of potential high-speed qualities with turning moment increase is limited to the following dynamic phenomena:

– probability of lower track wheel derailment from a caterpillar track of the faster running treads;

– the track coming off from driving sprocket of the slower running treads in the transient processes of going into a curve (the so-called a track rail problem);

– conditions of sizing into a limited corridor due to deflection in the trajectory from the assigned one, which is caused by phase lag of response to a driving input due to an intensive curvature change, especially on the routes with limited visibility of concealed bends;

– transitional speed is limited by inadvertent “quick”, non-compensated by the driver, deviations of azimuth angle.

All this leads to the fact that even an increase in power-to-weight ratio of HTV by 33 % doesn't give a due transitional speed gain. This article is devoted to analyzing dynamic phenomena, which reduce high-speed qualities of HTV in a turning mode, and to defining the ways of overcoming their effects.

The probability of lower track wheel derailment from a caterpillar track of the faster running treads occurs while moving over damageable ground. On the drift border when centrifugal acceleration $a_п$ levels off according to the road holding properties μg ($a_п \to \mu g$, wherein μ is a coefficient of resistance to rotation, g is gravity acceleration) track skidding ("drifting") in a sideways direction up to 1 m, accompanied by tearing layers of earth up, by bulldozerizing it, making borders on the ground up to 60 … 80 mm deep on the slower running tread side and up to 100 … 140 mm on the faster running tread side. Edge formation does not allow the vehicle to further sideways displacement with lateral acceleration effects up to 10 … 11 m/sec^2. Part of the removed earth gets on the track and is compacted by the front track wheels. Depending on the surface properties and track self-cleaning capacity the height of the earth layer on the track run can be comparable with height of earth crests. At a certain height of the earth layer lateral forces lead to lower track wheel derailment jamming up the caterpillar tread. It deprives the vehicle of its mobility, destroys tires of track wheels, and deforms balance weights. Decrease in probability of lower track wheel derailment is reached by constructive measures – by using doubled lower track wheels, by choosing geometrical parameters of the track shoe guide as well as by decreasing speed by the driver.

Driving along rather smooth roads with little deformable surface – with a coating, on frozen or rocky ground, formation of edges in a turning mode doesn't occur. However, lateral accelerations during transient processes of turning, which are determined by road-holding coefficient while starting, reach 6 … 8 m/sec^2. Thus, probability of lower track wheel derailment is limited, except for the cases of a side impact on caterpillars from a hard obstacle. But in such conditions, especially for the vehicles equipped with caterpillars with metal-rubber mounting (MRM) which curling stiffness is limited, the probability of the track coming off from the track driving sprocket of the slower running treads increases. Despite the complex nature of the phenomena, the consequences of the track coming off are the same as mentioned above. The track coming off during transient processes in a turning mode is explained as follows. Under the influence of traction and centrifugal forces the stretching of lower and upper track run parts occurs [3]. At the transit position from lower treads to the upper track run, the speed of caterpillar parts increases from 0 to two-fold speed rate $2V$, which is accompanied by track lengthening, which breaks their gearing with driving sprockets. In addition, under the influence of sideways forces during the turn of the vehicle bending of the track with MRM occurs in the horizontal plane about an angle $\Delta\gamma = n_{\text{тр}} \cdot \operatorname{arctg}(\Delta/t_{\text{г}})$. For a vehicle of 19 tons in weight, with track pitch of $t_{\text{г}}$ = 140 mm, the bend of the part from the last lower track wheel up to the track driving sprocket (the number of tracks $n_{\text{тр}}$ = 7, deflection of MRM of one track is $\varDelta$ 8…10 mm) makes $\Delta\gamma$ = 32…40°, which sets out the alignment of drive sprocket axle and track link pins (pin teeth). Linear deflections of track belts lead to track curve on the driving sprocket and gearing “skip”, and bend deflections are responsible for the track coming off.

In references [3] it is considered that a certain tightening of the slower running track in a turning mode implemented previously by the driver or continuously by automatic control system (ACS), should prevent derailment. However, with threefold increase in track tension force it was not possible to reach the required effect because of considerable pliability not only of the track run but also of the suspension system (for cushioning) as far as the upper track run doesn't stretch in this case. Besides, high speed of the ACS, for example, in drive designs with hydro pneumatic cushioning system while simultaneously accomplishing functions of track tightening and hydro pneumatic spring blocking doesn't provide ride comfort. In this connection an effective way of decreasing probability of the track coming off in a turning mode without decrease in speed is creation of driving techniques, which limit centrifugal accelerations during transient processes of turning.

The centrifugal acceleration value during controlled motion ($\alpha_{\text{пт}},\ \alpha_{\text{шт}} \neq 0$) is estimated from the second equation of the system (2.50) [2]:

$$\dot{V}_{Y} = V\left(\alpha_{\text{пт}}\right)\cdot\omega\left(\alpha_{\text{шт}},\alpha_{\text{пт}}\right) - \left(\sum P_X \sin\beta + \sum P_Y \cos\beta\right)/\,m\,,$$

wherein $V\left(\alpha_{\text{пт}}\right)$, $\omega\left(\alpha_{\text{шт}},\alpha_{\text{пт}}\right)$ is translational and angular speed while controlling fuel feed $\alpha_{\text{пт}}$ and steering $\alpha_{\text{шт}}$;

$\left(\sum P_X \sin\beta,\ \sum P_Y \cos\beta\right)$ is force projection of longitudinal X-axis and transversal Y-axis ;

β is a side angle; m is vehicle weight.

While driving with a high speed during transients centrifugal acceleration depends on overcontrol, overshoot and angular speed in many respects. Hence, constraint of centrifugal accelerations in dangerous conditions can be reached by a certain adjustment of driver’s input.

While driving along the roads with intensive curvature change the accuracy of a trajectory is determined in many respects by phase response lag of a driver’s input [1]. Because of the phase lag the vehicle does not have time to be turned about the required angle towards the tangent to the required trajectory of the mass center and does not negotiate the change in the direction of limited road width. The possibility of reducing the phase lag at the first stage is determined on the basis of qualitative analysis of the simplified model of driving, when the turning moment Mп($\alpha_{шт}$) is applied to the driving sprockets, i.e. without considering inertial and elastic properties of multidimensional SGS. The model is described by the differential equation of the first order:

$$J_z \dot{\omega}_п + k_м \omega_п = M_п(\alpha_{шт}),$$

which in Laplace transform S with zero starting can be presented as follows:

$$(T_м s + 1)\omega_п = k_п(\alpha_{шт}),$$

wherein: $T_м$ is a response time, $T_м = J_z / k_м$, $k_м$, $k_п$ are the coefficients of moment of resistance and of turning moment respectively, $k_м = M_c/\omega$, $k_п = M_п/k_м$.

Transition function and the phase-frequency characteristic are determined by the equations:

$$\omega_п(t) = k_м\left(1 - \exp\left(\frac{-t}{T_м}\right)\right),\ \varphi(\omega) = -\mathrm{arctg}\left(T_м \omega\right).$$

Thus, acceleration intensity at entering a curve and the phase-frequency characteristic do not depend on the turning moment but they are determined by a vehicle response time $T_м$. The size of the turning moment is a required but not sufficient condition of increasing the dynamic qualities of vehicles. With its sufficient value it is obviously possible to reduce phase response lag by entering a forcing link into the SGS, for example, with consecutive engagement of a differentiating link with the transfer function ($T_к s$ + 1). While engaging a forcing link the response to harmonic disturbance at the exit of the differential device also will be harmonious but with a leading phase $\varphi_к$:

$$\omega_к(t) = \omega_к \sin(\omega t + \varphi_к);$$

wherein: $\omega_к$ is reaction amplitude, $\omega_к = k_к z\omega/\cos(\varphi_к)$, z is harmonic disturbance amplitude, $\varphi_к$ is a phase, $\varphi_к = \mathrm{arctg}(T_к \omega)$.

By choosing the invariable $T_к$ it is possible to provide the required prediction of a signal of the turning moment at the electronic block input of the second control channel of PHD. For example, Sauer (S&SMB)'s PHD is produced with two control channels — mechanical and electronic with proportional control. The latter allows for controlling PHD according to the feedback control signal of ACS, of redundant and remote control.

Transitional velocity on a road with limited width and road-holding properties (damp concrete, ice-covered road) is limited by sizing if there are “fast” angular speed deviations in the frequency band of 0 … 12 Hz (fragments of realization of an angular speed deviation, fragments of a certain compensating control and spectral density of processes are given in [4]). The control error isn't compensated by the driver (response frequency of the driver < 1 Hz). Numerical characteristics of deviation value are determined according to the observed data of the stochastic function of azimuth angle deviation. When the vehicle in motion the deviation of angular speed is measured and its spectral density $S_\omega(\omega)$ is determined. When we have convergency of spectra of the coordinate and its derivative the root-mean-square deviation of the azimuth angle $\Delta\theta$ is estimated according to the formula:

$$\sigma^2_{\Delta\theta} = \frac{1}{\pi\omega^2}\int_0^\infty S_\omega d\omega,\ \text{a}\ \Delta\theta = \pm 3 \cdot K_\omega \sigma_{\Delta\theta}.$$

At high speed the driver’s control inputs are erroneous and lead to the growth of deviation of the azimuth angle and to a relative decrease in speed on conditions of sizing to the limited corridor.

These trajectory deviations can be minimized by installing a correcting device – a proportional integrating link. In such a system an output signal contains components proportional to desynchronization and to an integral of desynchronization:

$$\omega_{к} = k_{к}\left[\Delta\omega_{вх}(t) + \frac{1}{T_{к}}\int_{0}^{t}\Delta\omega_{вх}(t)\,dt\right].$$

In the limit, the steady-state error of control in such a system has final value $\Delta\omega = \Delta\omega_{вх} / (1+K_{р})$ and it decreases with the increase of the gain factor $K_{р}(M_{п})$ of the open-loop system.

However, introduction of an integrating link in control law reduces stability of the automatic control system and increases delay in resultant signal operation (the turning moment). To reduce such lag a desynchronization derivative is simultaneously introduced in control law, i.e. a proportional Integra-differential contour is synthesized.

On the basis of the results of the analysis of vehicular motion model with determined character of disturbances the principle possibility of reducing restriction effect and realizing potential high-speed qualities with enhancement of dynamic properties of SGS is defined. The requirements to the automated system have been formulated, in particular, to create forcing control, to compensate fast deviations, and to reduce recurrence of steering gear engagements by the driver. The tests of the pre-production vehicle with the breadboard model of PID of the correcting device of the steering gear system along the test snake-like route with half wavelength ΔS= 30…50 m have showed that average speed has increased up to 14.3 % with decrease in the number of engagements from 37 up to 25 per km of the distance. While driving along a soil road with a random change of trajectory curvature the average speed increases by 12…16 %, the number of steering gear engagements decreases by factor 1.5…1.8.

Conclusions

1. To reduce the probability of occurrence of the phenomena, which limit mobility of power-driven HTV (High-speed Tracked Vehicles) in a turning mode, such as track wheel derailment from the track run of the faster running treads over deformable ground, caterpillar coming off from MRM from the driving sprocket from the lower running treads on the roads with little deformable ground as well as meaningful measures for increasing stability of the track belt, it is necessary to restrict centrifugal accelerations of HTV turning and adjust a driver's inputs creating steering gear automated systems.

2. Increase of the turning moment providing for the vehicle to turn with the required acceleration, is a necessary but not sufficient condition for reducing phase lag of response to a corrective input and for compensating a steady-state error of control – "fast"(non-compensated by the driver) deviations limiting vehicle mobility due to the conditions of sizing to the roads of insufficient width with low road-holding properties.

3. Increase of vehicle mobility in a turning mode with a sufficient value of the turning moment (with determined disturbance) is reached by enhancement of dynamic properties of SGS – through the synthesis of integra-differential correcting devices. In a common case of driving when a trajectory curvature changes in a random way the quality of transients, reduction of a response phase to a corrective input and trajectory accuracy with limiting horsepower inputs for compensating deviations are reached by the synthesized optimum control without full awareness about disturbance forces.

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