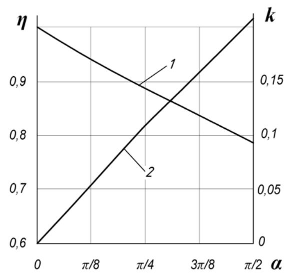

Рис. 7. Изменение показателей, характеризующих величину сил второго рода, в зависимости от угла обхвата при движении состава по кривой: **1 –** $\eta = (\alpha)$ **; 2 –** $k = (\alpha)$ **.**

Pic.7. Changing of indices that characterize values of forces of secondary order, in dependence on the angle of contact during train moving in curve: 1 – $\eta = (\alpha)$ **; 2 –** $k = (\alpha)$ **.**

Вывод очевиден: мотор-вагонная схема состава практически свободна от возникновения сил второго рода.

Представленные исследования еще раз доказывают перспективность модульной схемы комплектования состава и неэффективность тяжеловесных грузовых поездов с головным локомотивом (см. [5]).

Показав закономерности возникновения сил второго рода при движении поезда по кривой, автор не претендует на высокую достоверность полученных цифровых значений η и k, поскольку явление проскальзывания не равноценно абсолютному скольжению. Необходимы экспериментальные исследования в отношении определения фактической величины $\mu_{ск}$ в паре гребень – боковая грань головки рельса.

Измерение данного показателя не требует изготовления дорогостоящих установок. Это может быть выполнено в результате натурных испытаний с использованием штатной измерительной аппаратуры.

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THE TRAIN IN CURVE: ADDITIONAL POWER LOSSES

Alexandrov, Igor C. *– D. Sc. (Tech), professor of Vologda State university, Vologda, Russia.*

ABSTRACT

The article assesses relationship between friction forces in the contact area of wheelset and rail and the features of track curve. The study has been developed on the basis of Euler formula that establishes a ratio of forces in a pair rope – cylinder (capstan). Theoretical analysis argues under certain conditions in favor of positive outlook of modular trains (see also the article by the same author in previous issue of Mir Transporta (World of Transport and Transportation) Journal, 2013, Vol. 49, Iss. 5, pp.28–37 taking into account editorial remark on the necessity of comprehensive study of the subject).

ENGLISH SUMMARY

Background. *The motion of rail trains in curves causes additional power losses and wear and tear of wheelsets and rail heads. There are regulations that govern construction of track curves providing for velocity and train type [1, 2]. The methods to calculate the elevation of exterior rail permit compensating lateral impact of centrifugal force that influences train motion in curves. The process of compensation with the help of inclination of track to the turning side is described with the help of pic.1, formulas of physics laws (1). Inclination helps to avoid impact of lateral centrifugal force and conicity of the surface of wheels rolling permits to avoid slipping in the curve. But the real intensive wear and tear of a rail head and of a wheel flange (Pic. 2 and 3) show that those instruments are not sufficient to neutralize the negative effect there-of.*

The process of wear and tear can be explained as follows. The main part of the wheel, being in contact with the rail on the rolling surface, receives peripheral speed which is very close to transportation speed of a wheel set, and the resistance of motion can be evaluated through the value of the rate of rolling friction. The wheel flange, which contacts lateral face of rail head, has peripheral speed that considerably exceeds transportation speed of wheelset (Pic.4). Consequently the slipping arises between the bodies in contact and this phenomenon has to be evaluated through sliding friction rate.

According to tribological engineering studies [4] the rate of sliding friction is by far higher than the rate of rolling friction, and that is the reason for enlarged wear and tear of wheel flange and lateral face of rail head. The resistance to motion of the train in curves causes necessity to increase the locomotive traction as compared to traction at the straight track.

Objectives. *The task is to find alternative solutions to the problem of train motion in the curves besides increasing traction forces of locomotive and to minimize power losses.*

Methods. *The author focuses on the study of the process of transmission of traction force from locomotive to wheelsets during which the output flow is transformed. The article considers train as a kinematic chain (it was studied in [5]), using Euler formula and introducing the notion of the forces of secondary order.*

Results. *The motion of the train in the curve maintaining target (calculated) speed is impossible in running-out regime, neither in braking regime. So the maintenance of calculated speed is only possible in traction regime, but this regime results in other (additional) lateral forces that resist to the motion of a train headed by tractive locomotive.*

The forces of reaction of rail track that ensure the turning of the train act strictly in horizontal plane. This action is produced from the side of lateral face of rail head towards flange of the external wheel, and is transmitted through area of contact B (Pic.4) where slipping force arises. We can name those forces of resistance to motion forces of secondary order. The emergence of forces of secondary order doesn't depend on velocity of the train. They appear even when the train moves with the speed of a pedestrian when we can disregard centrifugal force. Those forces cannot be compensated by inclination of track neither by any other tool, as avoiding them we exclude the possibility of turning itself.

The forces of secondary order appear because the vector of traction effort of locomotive P is permanently changing its vector along the train which is moving in the curve (Pic.5). The change of direction of force can be caused only by another exterior force and this process is certainly followed up with energy loss. In that very case this exterior force is anything other than the force of reaction of the track R_p*. It is a feature of turning of all inland vehicles.*

But the train has a feature which is not characteristic of any other inland vehicles. If we have a train consisting of e. g. 100 wagons then it can have 400 wheelsets. Then the vector of traction effort will change its direction 400 times (Pic.5).

It is evident that there is no sense to show transformation of traction effort P as discrete function of number of wheelsets. But it is allowable, applying notion of infinitesimal, to present change of P in the form of continuous function of length of a train moving in curve. In that very case it is possible to use solved problem presenting train as a rope, which contacts with a part of cylinder surface – curve of rail track, using Euler's formula (2). This ratio is established for static system.

We can proceed with a little manipulation with that system, by getting it out of static state, by reducing confining force by a value ΔQ*. Then the rope will move relatively to immobile capstan. The friction conditions in the pair rope – capstan will change. The friction rate will reduce as [Euler and 4] friction rate of quiescent state is considerably higher than the rate of slipping friction:* $\mu > \mu_{CK}$ *.*

The new state of the system can be presented as:

$$Q - \Delta Q = P \cdot e^{-\mu_{ck}\alpha}; \; Q - \Delta Q = Q_{дв},$$

where $Q_{дв}$ *– value of effort. That ensures system motion with permanent velocity.*

So we received a transmission mechanism and its power efficiency can be assessed with coefficient of efficiency (η *), which is normally assessed by ratio between power index at the issue of transmission mechanism and the similar index at the entry. Let's use forces* $Q_{дв}$ *and P as power indices:*

$$\eta = Q_{дв} / P = 1 / e^{\mu_{ck}\alpha}. \qquad (3)$$

It is possible to use index of relative losses during transmission: $k = 1 - \eta$ *. Then, knowing value of traction effort* $P_{пр}$*, necessary for motion of a train on a straight track (*$P_{пр}$ *is found by regular traction calculation), it is possible to determine the value of additional traction effort* ΔP*, necessary to overcome the forces of secondary order while moving in the curve:*

$$\Delta P = kP_{пр}. \qquad (4)$$

The approximated values after calculation (if friction rate in the contact area flange – lateral face of rail head is $\mu_{ck} = 0{,}15$ *(according to [4] it is the value of steel-steel slipping friction); curve has angle of contact* $\pi/2$ *(Pic. 6)) are:* $\eta = 0{,}7901$*;* $k = 0{,}2099$*.*

Now if instead of a train headed by a locomotive, we'll use a train consisting of two modules, we'll have angle of contact for every module $\pi/4$*, and* $\eta = 0{,}8889$*;* $k = 0{,}1111$*.*

With four modules ($\alpha = \pi/8$ *)* $\eta = 0{,}9428$*; k=0,0572.*

Pic.7 shows calculations as chart.

Conclusions. The study shows good outlook for modular scheme of trains and relatively low efficiency of freight trains with head locomotive (see [5]).

Discussion. *Having demonstrated laws of forces of secondary order for train moving in the curve, the author does not pretend to have achieved high faithfulness reliability of numerical values of* η *and k, because slipping phenomenon is not equal to absolute sliding. It is necessary to obtain results of experimental studies to determine actual value of* μ_{ck} *in the pair of flange – lateral face of rail head. Measuring of that value will not demand expensive devices and can be realized with ordinary measuring tools.*

Key words: *railway, wheelset, rail, curve, friction forces, power losses, Euler's formula.*

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Координаты автора (contact information): Александров И. К. (Alexandrov I. C.) – alex@mh.vstu.edu.ru.

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