

# Analysis of vibrational load influence upon passengers in trains with a compulsory body tilt

D Ya Antipin<sup>1</sup>, V V Kobishchanov<sup>1</sup>, V F Lapshin<sup>2</sup>, A S Mitrakov<sup>2</sup>  
and S G Shorokhov<sup>1</sup>

<sup>1</sup> Bryansk state technical university, 7, 50-letiya Oktyabrya bul., Bryansk, 241035, Russia

<sup>2</sup> Ural State University of Railway Transport, 66, Kolmogorova str., Ekaterinburg, 620034, Russia

E-mail: adya24@rambler.ru

**Abstract.** The procedure for forecasting the vibrational load influence upon passengers of trains of rolling stocks equipped with a system of a compulsory body tilt on railroad curves is offered. The procedure is based on the use of computer simulation methods and application of solid-state models of anthropometrical mannequins. As a result of the carried out investigations, there are substantiated criteria of the comfort level estimate for passengers in the rolling-stock under consideration. The procedure is approved by the example of the promising domestic rolling stock with a compulsory body tilt on railroad curves.

## 1. Introduction

The tendency of the development of passenger rolling-stock consists in a railway traffic speed increase and decrease of the travel time that will allow increasing the competitiveness in comparison with other types of passenger vehicles. The increase of the railway traffic speed took place mainly on the existing trunk-railways. The majority of trunk-railways are designed without taking into consideration the organization of speed and high-speed running, and the state of groundwork is an obstacle for the railway traffic speed increase of a passenger rolling-stock. The analysis of the world experience in the organization of modern passenger railway communications on existing trunk-railways has shown that the average route speed of railway traffic and a decrease of the travel time is obtained at the expense of application of the rolling stock with systems of the compulsory body tilt. The effect mentioned above is achieved at the expense of the speed increase while passing railroad curves without a safety level and a passenger comfort decrease. It is obtained through the compensation of centrifugal forces affecting the rolling stock and passengers due to the compulsory rolling-stock tilt on the curve inside of railroad curves.

Theoretically, the system of tilt control following comfort criteria described above must ensure such body tilt at which passenger ride comfort would differ little from the comfort experienced in common trains running at lower speeds. It is possible to do having introduced the idea of an ideal tilt at which the angle of a body slope, for instance, at the entry to the curve, must gradually increase in accordance with the increase of values of transverse acceleration and an angle of an external high rail increase. It will give an opportunity to obtain 'ideal' values of the passenger comfort index. Then, comparing the control system with an ideal case, it is possible to define its functioning quality.



Speaking of the efficiency of control system functioning, we should define clearly a basic aim and emphasize requirements reasoning from the procedure presented.

The functional purpose of the system of a tilt consists in ensuring a quick reaction to the changes in a railroad curve and an outer rail height, without triggering the system of a tilt at random imperfections when running along straight track areas. For this purpose, it is necessary to make a compromise between responsiveness to the beginning of easy and random imperfections on straight track areas.

## 2. Results and discussion

Basic demands made to the control system are:

1. Railroad change monitoring,
2. Computation of an essential angle of a tilt taking into account the assurance of comfort and safety,
3. System fault monitoring,
4. Speed control.

For tilt control systems, there are some different approaches. In general, these approaches could be combined into two different groups: monitoring of the change in the track geometry and a system using geo-location data.

Nullification is one of earlier control systems which tried to reduce a measured acceleration in a steady-state curve to zero. A feedback in this kind of a system is ensured by an accelerator installed in a body (an acceleration measuring device). An evident advantage of this system consisted in the fact that a sensor was located after the second stage of a suspension. This type of location acts as a mechanical filter of track random imperfections. But, a sensor location in a tiltable body can cause an interaction between the suspension and dynamic control that will result in problems of stability in the control system. The experience of this control system use has shown that the complete compensation of lateral accelerations is connected with a large speed of a tilt and does not ensure optimum comfort.

The investigations described in [1] have shown that in case of complete compensation of a centrifugal force, the effect of rocking by daylight is observed among passengers because of the non-coordination of information from a vestibular apparatus and an observed visual image. In other words, rocking arose because passengers saw a slope, but did not feel it. At the same time, the speed of turning and jerks increase a sensory conflict.

To reduce this kind of a phenomenon of rocking, it is assumed to limit the level of compensation at the level of 60-75% of the level of complete compensation.

As the development of the 'nullification' strategy became a strategy of 'command control' giving a possibility of partial compensation of accelerations. It is carried out through the introduction of an amplification factor which can change within the limits of 0 – 'the system is switched off' to 1 – 'complete compensation of unabsorbed acceleration'. This system is equipped with both an accelerometer and gyroscopes to increase sensitivity and raise a possibility of monitoring the outer rail height.

It should be noted that a similar effect can be obtained in a nullification system of control having introduced a reverse angle in a controller, but this method is more complicated in a fulfillment.

In the command system of control, the sensors have no suspension operation influence upon them as they are located on a bogie. It allows placing beyond a control loop and increasing the stability of the control system. But, because of rigid connections with a bogie, an accelerometer apprehends accelerations not only in curves, but also on random imperfections. It can result in the system triggering on straight areas of the track. It is possible to avoid the system spontaneous triggering through the introduction of Kalman's filter [2]. This filter is intended for the recursive after-estimate of the vector of state of a priori known dynamic system, that is, for the estimate of the current state of the system, one uses current measurements and a previous state of the filter itself. The filter introduction will reduce an effect of track imperfections for satisfactory passing through straight areas of the track, but will result in a delay of the control system triggering on curve sections of the track. To eliminate this drawback, the command control can be supplemented with the principle of the leading

triggering used in rolling-stock X2000.

In the control system, formed according to the principle of advance, a signal, received from sensors installed on bogies of head cars, is transmitted in a digital way to the following cars with a corresponding time delay. For this type of the system it is necessary to take into account the speed and the direction of motion.

The drawback of this system is a complex procedure of the fulfillment and the necessity of the information transfer between cars. Besides, in this kind of systems, a head car is usually excluded from the operation of the system, or makes it with delay. The solution of the problem mentioned is the use of the control system based on the geo-positioning similar to that used in trains of the Japanese railroad company 'JR Central'.

In such control systems, an on-board computer is used with preliminarily recorded information of curve sections of the track, including a track curvature, an outer rail height and so on. The system is formed on the essential information transmission from a database to the device of a body shift on reaching an entry point of a curve section of the track by a rolling-stock. The main problem of this type of a control system is the definition of an exact position.

In the places of the beginning of a track curve section, a road mark is installed, approaching to which an on-board computer reads essential information and transmits it to the device of a body shift, at the end of a curve section, the on-board computer receives information about the end of a body tilt from other mark. This system for tilt control ensures considerable smoothness of work in track curve sections and stability in straight ones independently of random imperfections. A drawback consists in high cost, availability of an essential infrastructure and impossibility of the rolling-stock use on other routes without preliminary training. Besides, when using track marks, there is likelihood that the information will not be read from a stationary transmitter. To increase reliability, the tilt control system can be equipped with an odometer reading a car travel. It will allow controlling a route traversed between track marks. A drawback in the use of the odometer consists in error accumulation.

It is possible to eliminate the drawback of the odometer by means of the introduction of the GPS/GLONASS systems of geo-positioning into the system of control. The application of such systems allows defining absolute coordinates of a rolling-stock, which makes it possible to use a partial failure of track marks. Having considered the control systems described in accordance with the criteria of choice, it is possible to draw a conclusion of the usefulness of application of one of two systems functioning either on the principle of advance or on the principle of geo-positioning for a domestic rolling-stock. For existing tracks, it is offered to use a system formed by the principle of a leading triggering and for new tracks — allowing the use of automatic train monitoring — a geo-positioning system supplemented with the GLONASS system.

When using a rolling-stock equipped with the systems of a compulsory body tilt, a significant problem consists in the control of passenger safety and comfort when passing curve sections of the track. The criteria for passenger safety and comfort consist in:

- a) The level of non-absorbed accelerations affecting a person.
- b) The elimination of rocking effect.

For a motor-car rolling-stock operated on domestic railway lines, the criterion of safety and comfort can be a level of transverse non-absorbed acceleration and functioning at the level of an axle box during the motion along the curve track sections, not compensated by the outer rail height [3] and an index of motion evenness in vertical  $W_z$  and horizontal  $W_y$  cross directions [2].

In accordance with [3], a maximum admissible value of non-absorbed acceleration makes  $0.7 \text{ m/sec}^2$ . On the tracks where speed trains and passenger rolling-stocks are operated with updated dynamic characteristics with the permission of RZhD, an admissible value of  $a_{np}$  can be increased up to  $1.0 \text{ m/sec}^2$ . The results of complex psycho-physiological investigations of passengers carried out by VNIIZhT jointly with VNIIZhG have shown that when increasing a non-absorbed acceleration above  $0.8 \text{ m/sec}^2$ , an increasing degradation of a functional state and availability of vivid signs of a subjective discomfort were observed among the majority of passengers [4]. At the same time, the safety of passengers is ensured up to the level of a non-absorbed acceleration of  $1.2 \text{ m/sec}^2$  [4]. In

work [5], it is pointed out that when exceeding the limit of  $2 \text{ m/sec}^2$  by horizontal accelerations affecting a passenger, sitting in an armchair, he begins to feel discomfort at accelerations of above  $3 \text{ m/sec}^2$ . For standing passengers, the admissible accelerations are those which do not exceed the limits of  $0.7\text{--}1 \text{ m/sec}^2$ .

In European Standard EN 13803-1 [6], limit values are the regulated non-absorbed quasi-static cross accelerations of a body and the units of a rolling-stock in the range of  $1.0\text{--}1.5 \text{ m/sec}^2$ .

The indices of motion evenness are defined through the dependences recommended by GOST RF 55495-2013 [7]:

- for vibrations acting in a vertical direction:

$$W_z = 4.346 \tilde{a}_k^3; \quad (1)$$

- for vibrations acting in a horizontal cross direction:

$$W_y = 4.676 \tilde{a}_k^3, \quad (2)$$

where  $\tilde{a}_k$  – the quadratic mean value of corrected vibro-acceleration in the  $k$ -th range of motion speed,  $\text{m/sec}^2$ .

The indices of motion evenness in vertical and horizontal directions must not exceed the value of 3.25.

For the rolling stock equipped with a system of the compulsory body tilt, the level of comfort is defined according to the European procedures described in CEN12299 [8] and materials of Japanese specialists [9].

Within the bounds of Standard EN 12299, let us define the passenger comfort in straight track sections using a coefficient of average comfort,  $N_{MV}$  [8], defined through dependence

$$N_{MV} = 6 \cdot \sqrt{(a_{XP}^{Wd})^2 + (a_{YP}^{Wd})^2 + (a_{ZP}^{Wd})^2}, \quad (3)$$

where  $a_{XP}^{Wd}$  – accelerations affecting a passenger in the longitudinal direction;  $a_{YP}^{Wd}$  – accelerations affecting a passenger in the side direction;  $a_{ZP}^{Wd}$  – accelerations affecting a passenger in the vertical direction.

This coefficient takes into account accelerations affecting a person in all directions at the level of the floor.

To determine the percentage of passengers feeling discomfort in [8], the following dependence is used:

$$P_{CT} = 100 \left\{ \max \left[ A \left| \ddot{y}_{ls} \right|_{\max} + B \left| \ddot{\dot{y}}_{ls} \right|_{\max} \quad C; 0 \right] + \left( D \left| \dot{\varphi}_{ls} \right|_{\max} \right)^E \right\}, \quad (4)$$

where  $\ddot{y}_{ls}$  – the side acceleration of a body,  $\text{m/sec}^2$ ;  $\ddot{\dot{y}}_{ls}$  – the side acceleration change of a body during 1 sec,  $\text{m/sec}^3$ ;  $\dot{\varphi}_{ls}$  – the angular velocity of a body,  $\text{rad/sec}$ ;  $A, B, C, D, E$  – constants admitted in accordance with [8].

In accordance with [9], the level of discomfort according to a four-point scale is defined through the following dependence:

$$TC_T = a\ddot{y} + b\ddot{\dot{y}} + c + d\ddot{\varphi} + e, \quad (5)$$

where  $\ddot{y}$  – the side acceleration of the body,  $\text{m/sec}^2$ ;  $\ddot{\dot{y}}$  – the side acceleration change of the body during 1 sec,  $\text{m/sec}^3$ ;  $\dot{\varphi}$  – the angular velocity of the body,  $\text{rad/sec}$ ;  $\ddot{\varphi}$  – the angular acceleration of the body,  $\text{rad/sec}^2$ ;  $a, b, c, d, e$  – constants adopted in accordance with [9].

For the rolling stock equipped with the system of the compulsory body tilt, it is necessary to take into account the effect of rocking. The researches of this effect by European scientists [4] have shown that the most common reason for its arising is a conflict of the human sensor system. For example, during the complete compensation of a centrifugal force, passengers feel the absence of corresponding accelerations in the daytime as the effect of rocking because of non-coordination feeling in a body position and a visual image [8, 10]. Spreading of sickness depends on a number of factors: physical properties, duration of an effect, human susceptibility, the task to be carried out and other factors.

The effect of passengers rocking during the curve track section passing is estimated in accordance with [10], on the basis of the definition of a rocking dose defined through dependence

$$MSDV_z(t) = k_{MSDV} \cdot \sqrt{\int_0^t a_{wf}^2(t) dt}, \quad (6)$$

where  $a_{wf}$  – the frequency-weighted vertical acceleration,  $\text{m/sec}^2$ ;  $k_{MSDV} = 1/3$  – the coefficient for mixed population of grown-up men and women incapable of the adaptation.

On the basis of a rocking dose, it is also possible to prognosticate a level of indisposition. The value of ‘rate of illness’  $IR(t)$  is graduated according to the scale from 0 (‘I feel good’) up to 3 (‘I feel absolutely terrible’) and is defined through dependence [9]:

$$IR(t) = \frac{MSDV_z(t)}{50}. \quad (7)$$

In [11], there is a derived ‘neat’ dose of rocking  $ND(t)$  as a function of time taking into account the rise of the effect of rocking and recovery after it, which is definable through the dependence:

$$ND(t) = C_a \cdot \int_0^t A(\tau) \cdot e^{-C_L \cdot (\tau-t)} dt, \quad (8)$$

where  $A(\tau)$  describes a motion,  $C_a$  and  $C_L$  – constants.

In the procedures shown, the level of comfort is estimated on the basis of body accelerations of a unit of a rolling stock, taking into account only two passenger positions – ‘upright’ and ‘sitting’, whereas on the territory of the country, the revenue service of trains ‘Talgo 250’ with cars equipped with berths began.

The estimation of safety and the level of passenger comfort in the paper is carried out by methods of the mathematical modeling and computer simulation of rolling stock working with the use of anthropometrical models of mannequins.

a five-car local train equipped with air springs of a central stage of bogie suspension and a system of the compulsory car body tilt on track curve sections with an electric locomotive were analyzed as a test object.

The estimation of accelerations affecting train elements and passenger models is carried out on the basis of a solid-state computer model developed in the environment of the ‘Universal Mechanism’ software complex (Figure 1).

A model represents a two-level system including subsystems of the first level – a ‘head’ car, a ‘trailer’, and a ‘powered’ car, as well as subsystems of the second level describing functioning chassis and the automatic coupling device. The subsystems of the first level are formed with absolute solids describing inertial characteristics of a car body and connected with special power elements and hinges with the subsystems of the second level – ‘a bogie of a trailer’ and ‘an automatic coupling device’.

During a car body modeling, an actual location of heavy internal and external equipment and passengers is taken into account. Computer models of the ‘trailer bogie’ and ‘motor car bogie’ subsystems represent a system of absolute solids connected by power elements and hinges. The modeling of an air spring is carried out within the limits of the GENSYS model described in the digital Matlab/Simulink processor and integrated into a developed computer model with the use of the UM Control module of the ‘universal mechanism’ complex. On the basis of the data of body acceleration, the angle of slope is computed in the Matlab/Simulink program, a control effect is transferred to the model of an air spring changing the angle of the body tilt.

The modeling of a car motion is considered taking into account track micro-roughness. The formation of random imperfections is carried out on the basis of the spectrum density function, equivalent to a computed roughness in vertical and horizontal directions, defined for speeds of a car motion up to 200 km/h according to the procedure shown in RD 32.68-96.

For the estimation of dynamic influence upon passengers during a train motion, the solid-state models of car bodies were supplemented with computer models of anthropometrical mannequins of the Hybrid III 50<sup>th</sup> Male Dummy type.

Mannequins are located in different passenger places of a car, as well as in passages, platforms and service rooms in the ‘upright’, ‘sitting’ and ‘lying’ positions (Figure 2).

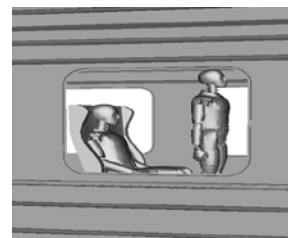
As a result of multi-version computations carried out, we defined maximum accelerations of axle-box units, car bodies, as well as dummy accelerations taking into account the ‘worst’ positions and places of location from the point of view of comfort assurance.

The analysis of results obtained has shown that transversal non-absorbed accelerations operating at the level of an axle-box at the motion along the track curve sections at speeds up to 200 km/h, do not exceed the recommended level [3]; the transversal accelerations of a car body correspond to the requirements of EN 13803-1 [6]. Dummy accelerations in a 'sitting' and 'upright' position do not exceed the recommended levels [5].

The estimation of motion evenness indices has shown their correspondence with the requirements of GOST RF 55495-2013 with considerable indices of reserve.



**Figure 1.** The solid-state computer model of the electric train:  
1 – 'head car' subsystem; 2 – 'trailer' subsystem;  
3 – 'powered car' subsystem.



**Figure 2.** The location of solid-state models of anthropometrical mannequins in a car body.

When estimating the comfort level on the basis of procedures recommended in [8-10], both accelerations of a car body and accelerations affecting computer models of mannequins were assumed as initial data.

The analysis of results of the passenger comfort level has shown that the results obtained when we use accelerations of car bodies by 10–45% higher than the results obtained with the use of dummy accelerations as initial data. The largest discrepancies are obtained for a passenger 'upright' position on the platform of a car near an entrance door taken as the position with the lowest level of comfort. The least ones were for the 'sitting' position in the medium row of a car in the armchair by a passage.

### 3. Conclusions

On the basis of the obtained results, it is possible to draw a conclusion about the correspondence of the design of a local train, driven by an electric locomotive, with the requirements of domestic and foreign regulation documentations and an expediency of the use of computer models of anthropometrical mannequins to specify the estimation of the passenger comfort level in trains equipped with a system of the compulsory car body tilt in track curve sections.

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