General principles of control method of passenger car bodies bending vibration parameters

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Abstract. Weight reduction of passenger cars is a promising direction of reducing the cost of their production and increasing transportation profitability. One way to reduce the weight of passenger cars is the lightweight metal body design by means of using of high-strength aluminum alloys, low-alloy and stainless steels. However, it has been found that the limit of the lightweight metal body design is not determined by the total mode of deformation, but its flexural rigidity, as the latter influences natural frequencies of body bending vibrations. With the introduction of mandatory certification for compliance with the Customs Union technical regulations, the following index was confirmed: "first natural frequency of body bending vibrations in the vertical plane". This is due to the fact that vibration, noise and car motion depend on this index. To define the required indexes, the principles of the control method of bending vibration parameters of passenger car bodies are proposed in this paper. This method covers all stages of car design – development of design documentation, manufacturing and testing experimental and pilot models, launching the production. The authors also developed evaluation criteria and the procedure of using the results for introduction of control method of bending vibration parameters of passenger car bodies.

1. Introduction
At present, when developing new passenger cars special attention is paid to providing comfortable environment for passengers, safe labor conditions of conductors, transportation profitability, reducing weight and improving security, operational reliability and durability of the train.

The parameters of bending vibration of passenger car bodies are one of the main factors (along with elastic-dissipative parameters of the running gear and track technical state), affecting the indexes of riding comfort and the characteristics of vibration inside the car. They depend on the geometric dimensions, mass, material and flexural rigidity of the metalwork. For equipped car bodies, the parameters of bending vibration also depend on the car layout, materials and assembly technique of thermal insulation and facing, mass and car interior layout. Besides, there is a dependence of bending vibration parameters on the conditions of body support (rigid or bogie swing suspension).

The problem of reducing passenger car weight is solved by either lightening the running gear and car interior, or by lightening metal body. Lightening metal body is achieved mainly through more efficient use of the material in the body design or through use of high-strength aluminum alloys, low-alloy and stainless steels.
2. Problem statement

As it is seen in the standard requirements, only one index is specified for an equipped body. As it is noted in works [1-3], it is not enough. In the case of deviations of the index "first natural frequency of bending vibrations ..." from the normative value, it is necessary to carry out expensive measures for modernizing the body. This will require partial disassembly of thermal insulation with the facing and the dismantling of interior equipment. In addition, it may be necessary to carry out additional calculations and tests. These procedures can delay the date of getting a certificate of conformity and the beginning of serial production for a long time. At the same time, there is a need to improve design documentation and re-approval.

Thus, on the basis of analysis of research results of body bending vibrations, experience in car operation and regulatory requirements, it may be noted that it is necessary to develop a control method of bending vibration parameters of passenger car bodies in order to guarantee meeting the standard requirements of car vibration characteristics.

Moreover, the method should cover all stages of car design, such as the stages of design documentation development, manufacturing and testing of experimental and pilot models and launching the production.

3. General principles and working steps

As mentioned above, the developed expert-testing-calculated (ETC) control method of bending vibration parameters of passenger car bodies in the vertical plane should cover all stages of car design. In this regard, it is proposed to carry out the following activities step by step:

1. the first part of the method should include the stage of design and development of design documentation and examination of the results obtained (expert-calculated part);
2. the second part of the method covers the stage of bench tests of the metal body and examination of the obtained results (bench-expert part);
3. the third part of the method covers a bench vibration test, dynamic running and sound-vibrometric test of fully equipped car on the ground (ground-expert part);
4. the fourth and final part of the method covers controlled operation (for at least one year) of the first rolling stock containing new cars, and examination of the results obtained (main-expert part).

During the first part of implementing the electric equipment maintenance and repair method (EIR method) it is necessary to:

a) receive the design documentation on the car where the dimensions and mass parameters of the body are defined, materials for the main load-bearing elements of the metal structure are selected and layout drawing of accommodation of passenger, conductors and interior equipment is developed, the mode of car body deformation from the normalized loads is calculated [7]. This calculation by all means includes the definition of: the area and moments of inertia of typical cross-sections, body flexural rigidity in the vertical plane, eigentone frequency of body bending vibrations, etc.;

b) analyse the results and the expert judgment of influence of material grade of frame elements, facing and set members, facing thicknesses of various body parts, location of the main body longitudinal members, their geometric characteristics on the frequency values of bending vibrations of body design, etc.;

c) obtain expert assessment of possible impact of the car design, the mass-dimensional parameters and the location of the primary internal equipment, working dynamic parameters of power equipment (undercar generators, diesel generators, compressors, fans, etc.) on the natural frequency of the body flexural vibrations.

For carrying out works under sub-items "b" and "c", it is necessary to develop an improved method for calculating the natural frequencies and shapes of the body vertical bending vibrations, taking into account the contour deformation of the body cross section and location of the most metal-intensive internal and outboard equipment. Works on making an improved method for calculating cars are held in the Institute and were tested while performing a specific work [8], [9].

The second part of this method covers the stage of the body bench tests and examination of the obtained results (poster-expert part). The second part of the EIR method starts after making the metal
body experimental or pilot model and its acceptance by the manufacturer’s Commission. When working on the second part of the EIR method, one needs to:

a) conduct bench static tests on examining the metal body vertical bending vibrations. Testing the metal body is carried out in two stages:
- directly to the metal structure of the body;
- the metalwork, loaded to a body gross;
b) conduct bench testing to examine the vertical flexural vibrations of a fully-equipped car body.

While carrying out tests under points "a" and "b" of the second part of the EIR method, one must define the following characteristics:
- body metalwork weigh and a fully equipped body;
- frequency of the first tone of vertical flexural vibrations and forms of its own vertical flexural vibrations of a metal body and a fully equipped body;
- body deflection under load gross;
- deformation of the body contours along the middle cross section;
- the body flexural rigidity;
- the coefficient of the internal resistance;
- logarithmic decrement of attenuation;

c) expert assessment of the bench tests results for car bodies and decision-making on the admission to the car final assembly, conducting acceptance testing and making ready car for the driving and maintenance tests.

A separate stage of the second part of the EIR method is the comparison of the calculated and experimental results and verification of the developed method for calculating the natural frequencies and the vertical bending vibrations shapes of bodies.

For carrying out works under sub-items "a" and "b" of the second part of the EIR method application, it is necessary to develop comprehensive programs and methods of bench tests to determine the parameters of rigidity and vertical bending vibrations of passenger car bodies. There are a number of methodology provisions developed and applied by members of the Institute [10].

Table 1 shows experimental results of determining the frequency of the first tone of flexural vibrations of the most typical passenger car fully equipped body, obtained at JSC "Tver Institute of car building" over the past 25 years.

**Table 1. Experimental results of determining the frequency of flexural vibration the first tone**

| The car model  | The car type | New equipment | Frame Material | Cushion Material | The body length, m | Experiment |
|---------------|--------------|---------------|----------------|------------------|-------------------|------------|
| 61-828 | Open compartment with armchairs | Air conditioning - - | Centre girder A 516-60 | Corrugation shape round | 23,976 | 33,60 | 10,0 |
| 61-850 | Compartment | Ecotoilet - - | variable cross-section | round | 23,976 | 32,85 | 10,3 |
| 61-4178 | Open compartment with armchairs | Material DD 11 (StW 22) | | smooth | 23,976 | 36,30 | 10,24 |
| 61-4440 | Compartment | Material AISI 375 | | trapezium-shaped | 24,976 | 43,96 | 8,5 |

The body tare, t: 33,60 / 32,85 / 36,30 / 43,96

Year of test: 1992 / 1993 / 1999 / 2013

The body grass weight, t: 38,525 / 38,47 / 42,96 / 48,76

Frequency, Hz: 10,0 / 10,3 / 10,24 / 8,5

Frequency, Hz: 9,34 / 9,52 / 9,41 / ~8,0

The body grass weight, t: 38,525 / 38,47 / 42,96 / 48,76

Frequency, Hz: 9,34 / 9,52 / 9,41 / ~8,0

Year of test: 1992 / 1993 / 1999 / 2013
The third part of this method covers dynamic running and noise vibrometric testing at the poligon or mainline railways (linear-expert part). The third stage is performed on a fully assembled car on a regular chassis which has passed acceptance tests. When conducting work on the third part of the EIR method, one needs to:

a) conduct dynamic running and noise vibrometric tests at the poligon or a dedicated section of the main railways. This is based on defining: the car body vertical accelerations, bolster, bogie frame and axlebox nodes, indicators of smoothness, sound and infrasound vibration levels inside the car, rail journey bump. For work on the third part of the EIR method, it is necessary to develop comprehensive programs and methods of dynamic running and passenger car noise vibrometric testing. The programme should include a methodology for determining the vertical track irregularities by measuring vertical accelerations on the journal boxes, chassis. While developing a comprehensive program, it is necessary to take into account regulatory requirements [11];

b) have expert evaluation of running passenger car dynamic and noise vibrometric test results and the decision on admitting the car in operation. For that, one defines influence of the undercarriage parameters, inside the carriage, and undercar equipment and the way quality to change the first tone frequency of the body flexural vibration as compared with the bench test results. When conducting the expert assessment of the tests on the line results, one evaluates the compliance of the smoothness indicators to the regulation requirements for the passenger car design, as well as the compliance to the requirements of vibration, sound and infra-sound levels across the frequency range; the path of a polygon or a selected section of the trunk railway.

As a separate stage, expert assessment of the influence is carried out on the above-mentioned work parameters inside the carriage or undercar equipment (diesel generators, compressors, fans, etc.).

The fourth (main-expert) and the final part of the method covers method-controlled operation (for at least a year) of the first trains formed from the new cars. The need for this part of the EIR method stems from the fact that in the process of exploitation, there is a change of some parameters in the car (within specified limits), which have an impact on the car dynamic and vibration characteristics (wear and roll stock of wheels, the change in the rigidity of the locking bolt rubber elements, spring pocket, etc.).

Conducting this part of the work in the EIR method is especially important in cases where the normalized performance of the dynamic and vibration characteristics obtained during the previous tests are close to regulatory or exceed them by no more than 5%.

To conduct a controlled operation, it is necessary to develop the program and methods of their realization. It is necessary to include the following in it:

- carrying out periodic inspections of the most "problematic" components and the car systems (on a quarterly basis or after a certain mileage);
- carrying out periodic survey of passengers and staff (quarterly or after a certain mileage).

Conducting a controlled operation should be carried out by specialists of the car manufacturer, a scientific research organization that conducted the greatest amount of acceptance and certification tests involving employees of operational services (the home depot and train crew).

Controlled operation has recently become one of the most important stages of evaluating the quality and reliability of the new generation passenger cars and their systems [13], [14].

4. Evaluation criteria and use of results

After completing each part of the EIR method, let us evaluate the results and define directions of their further use.

After completing the first part of the work of the EIR method, there are three possible directions for its continuation:

- the results obtained on metalwork (10-11 Hz) and the body under load gross (8-9 Hz) are compliant with the regulatory requirements [7] and the decision on constructing an experimental or pilot model of the metalwork is made;
- the results obtained for metalwork (less than 9.5 Hz) and the body under load gross (less than 8
hz) are non-compliant with the regulatory requirements [7]. In this case, there are developed technical solutions to bring performance up to regulatory forwarded to the developers for design and calculations in accordance with regulatory requirements;

- the obtained results on steel (over 12 Hz) and the body under load gross (more than 10 hz) are significantly in excess of regulatory requirements. In this case, one develops technical solutions for the reduction of metal design and brings performance close to the normative and passes it to the developers for design and calculations in accordance with regulatory requirements.

At the end of the second part of the work by the EIR method, it is also possible to have three directions for its continuation:

- obtained experimental results on metalwork (more than 10 Hz) and the equipped body with the gross mass (more than 8 Hz) are compliant with the regulatory requirements [7] and a decision about the car final assembly and acceptance tests fulfillment is made;

- obtained experimental results on metalwork (9.5 Hz) are non-compliant with the regulatory requirements [7]. In this case, the final assembly of the body is suspended and technical solutions are developed to bring performance up to regulatory requirements and they are urgently implemented in the tested metalwork. Then a repeated testing is held. In addition, there are adjustments of the calculation method used in the first part of the EIR method.

- obtained experimental data on metalwork and equipped body exceed regulatory requirements by more than 25%. In this case, a decision is made about the car final assembly and acceptance tests. In addition there is carried out an analysis of causes and activities are designed to bring the analyzed indicators to the regulatory requirements [7] for new bodies by reducing the thickness of cushion, load-bearing longitudinal frame elements, elements of transverse frame, etc., while not forgetting the previously performed calculation of the body VAT in the first part of the EIR method. Also there is carried out the adjustment of the calculation method used previously.

Upon completion of the third part of the work of the EIR method, there are three options for its continuation:

- obtained experimental results for dynamic running and noisevibrometric tests meet the requirements of all normative documents [7, 12]. Cars are recommended for serial production and the first trains of the mentioned cars are ready for the annual controlled operation (the fourth part of the EIR method);

- results obtained by certain requirements are not compliant with regulatory documents. In this case there are primarily developed technical proposals on bringing the car indicators to the standard due to the running parts. Separately there is specified the impact of the inside and undercar power equipment on the diagnostic variables. If necessary, a computational analysis is performed on the previously developed calculation method.

In case of impossibility of bringing the studied parameters to the standard due to the running parts and power equipment there are developed proposals to increase the body flexural rigidity.

After making changes in the car design to assess their effectiveness, there are carried out repetitive reduced dynamic running and noisevibrometric tests of the examined car.

In the case that the experimental results are compliant with the regulatory requirements [7, 12] with a large margin, a car is recommended for serial production and the results of the expert analysis must be entered in the information database of the EIR method.

The information obtained during controlled operation after the processing is recorded in the information database of the EIR method and used further to improve certain provisions of the foregoing methodological foundations of the method and to develop new models of cars.

Currently, the Institute has developed and applied certain provisions of the EIR method in carrying out acceptance and certification tests of new passenger cars [15, 16].

5. Conclusions

1. Weight reduction of passenger cars is a promising direction of reducing the cost of their production and increasing the profitability of passengers’ transportations.
2. By reducing the weight of passenger cars by decreasing the weight of the metalwork, the greatest effect is achieved through the use of high-strength aluminum alloys, low alloy and stainless steels.

3. Analysis of domestic and foreign experience in constructing and testing lightweight cars has shown that often the body weight reduction limit is not determined by the general stress-deformable state, but by the bending rigidity on which the first natural frequency of the body vertical bending vibrations depends.

4. The introduction of the indicator "the first natural frequency of the body vertical bending vibrations" in case of mandatory certification for compliance with the requirements of technical regulations of the Customs Union "About the safety of railway rolling stock" and "About the safety of high-speed rail transport" required to develop a control method of this indicator and the flexural rigidity of the car body.

5. For the practical application of the proposed EIR method, it is necessary to develop an improved method of calculating natural frequencies and forms of the body vertical flexural vibrations, comprehensive programs and methods of bench tests to determine the parameters of the body vertical flexural vibrations, comprehensive programs and methods of running dynamic and noise vibrometric dynamic tests of passenger cars, programs and methods of controlled exploitation.

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