где $\{\Phi\}$ – вектор форм колебаний для частоты ω.

Вектор формы колебаний обычно масштабируется для каждой моды, чтобы выполнялось условие

$$\{\Phi_i\}^T [M] \{\Phi_i\} = 1{,}0 \,, \qquad (5)$$

поэтому формы колебаний, например, на рис. 4, представляются в относительных единицах и показывают только соотношение между перемещениями различных частей системы.

Все расчеты выполнялись с использованием конечно-элементной модели, построенной по геометрической модели (рис. 1) в расчетном пакете «Patran-Nastran».

На рис. 4 и 5 показаны основные формы колебаний с частотами 50,4 Гц и 63 Гц, наиболее близких к формам колебаний, которые возбуждались в эксперименте. На рисунках видны деформации кронштейнов в увеличенном масштабе, чем подтверждаются колебания двигателей в эксперименте за счет деформаций кронштейнов и прилегающих участков рамы тележки.

Для сравнения в таблице 1 приведены значения расчетных и экспериментальных частот.

Как видно из таблицы, экспериментальные и расчетные значения частот отличаются не более чем на 6%. Это позволяет заключить, что построенная конечно-элементная модель не противоречит экспериментальным данным и ее можно применять при решении динамических задач.

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COMPUTED MODEL FOR TRACTION GEAR

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ABSTRACT

The article describes development of finite element model which doesn't contradict real unit and is intended for dynamic computation of traction engines of locomotives. The article argues in favor of use of the method of finite elements because it allows reflecting elastic, inertial and dissipative features of dynamic systems. The approaches towards simulation of the bogie with the account for springing, traction engines, braking cylinders at the edges of the frame are substantiated. The described model of «frame bogie – traction engines» is verified for conformity with experimental data.

ENGLISH SUMMARY

Background. *Modern electric locomotives, capable to achieve high speed, use two-axle bogies with welded frames. The welded bogies are more elastic as compared to cast bogies. Positioning of massive elements of traction gear, like traction engines, gear, engine-gear units, on the welded bogies makes it necessary to consider a bogie as elastic structure, functioning as elastic support base for the elements of traction gear.*

Objective. *In order to neutralize possible vibrations of the elements of gear on an elastic base it is necessary to study dynamic features of such systems. It is also necessary to develop method of computer-aided simulation that permits to optimize frame design in order to achieve the required strength and to minimize the use of materials.*

Methods. *As the total weight of traction engines and gears exceeds or is equal to frame weight, it is necessary to account for elastic and dissipative features of the frame, considered as distributed system, and in some case for the mentioned features of gear elements as well.*

During the study of dynamic features and especially during computation of own frequencies and vibration forms of similar systems it is necessary to apply methods of the theory of elasticity, which are realized within the method of finite elements and in software. This method allows taking into account of inertial and dissipative features of dynamic systems and their spatial distribution.

Results. *Vibration equations for similar systems are generally described by matrix (1), where* $[M],[B],[K]$ *are respectively matrix of weight, dissipation and rigidity of the system,* $\{\ddot{u}\},\{\dot{u}\},\{u\}$ *are vectors of acceleration, velocity, displacement of finite elements of a system;* $\{P\},\{N\}$ *are vectors of external forces and non-linear elements.*

The study of dynamic systems supposes solution of a set of problems, comprising determining of proper frequencies, figures, vectors, oscillation forms of a dynamic system (as well as of internal features, structures, possible resonance frequencies).

As one can see, the above mentioned equation is necessary to plot characteristics of weight, dissipation, and rigidity. It can be done on the basis of technical specification, or experimentally, if a prototype of studied system exists.

In real practices in order to reduce the volume of the problem it is necessary to optimize the dimension of a system under the study. In the described case it is necessary to create a computed model of a system intended for a study of joint oscillations of traction engines and of a bogie frame. If the problem is stated in such a manner, we need to consider main elements of a system and the elements, which are not considered therefore, are to be plotted through limiting conditions, determined by character and kind of reactive forces of the elements of a more complex system interacting with the system under the study.

The system «bogie frame – traction engines' interacts with wheelsets by box springing and with the body by central springing. Threshold conditions can be plotted as rigid mounting of the frame in the places of location of the springs, or it can be simulated through simulation of springing.

Proper frequency of flexural mode of bogie's oscillations can be computed according to Rayleigh law [1] (if $l=2,85\,m$; $m=2214\,kg$; $l=2,45 \cdot 10^{-4}\,m$; $E=2\cdot 10^{11}\,\frac{H}{м^2}$) and then to determine equivalent rigidity of the frame by the same formulae (2):

$$f_1 = 0{,}498\pi\sqrt{\frac{EJ}{ml^4}} \qquad (2)$$

Computation of equivalent rigidity of a frame for oscillation frequency equal to $f_1 = 28{,}656$ Hz has shown that the rigidity of the frame has the same order of magnitude that the total rigidity of box springing, that is why it should be considered in computed model.

Pic.1 shows geometrical computed model of a frame of the bogie of electric locomotive EP10 with springing, traction engines and braking cylinders which also should be considered, as they can influence the values of own frequencies and character of vibration form of the frame.

Experimental data necessary for verification of the computed model were taken from testing protocols of electric locomotives EP10 (held by VEINII and MIIT). Own frequencies of vibration of traction engine on the elements of bogie frame were actuated by blows in vertical and lateral direction relatively to the axle of the track. The frequencies were determined by processing recordings of accelerations and tensions in big mounting bracket of traction engine as well as by processing data on starting and braking modes.

Experimental data concerning actuation of the vibrations caused by blows into the body of the frame are shown in pic.2 and explained in the text.

The pic.3 shows fragments of recordings of torsion moment at the body of traction engine during locomotive starting and its movement with permanent speed, that are explained in the text.

As the result of processing of experimental data the researcher determined frequencies of joint oscillations of traction engine and bogie frame which are in the range of 49–63 Hz (depending on actuated form of vibration). Oscillations of traction gear have frequency of 10–11 Hz, and oscillations of traction engine together with bogie frame, caused by track irregularities, have 36–39 Hz frequency (depending on conditions of engine mounting at the bogie frame).

In order to compute dynamics of forced oscillations of dynamic systems it is necessary to account for damping which is determined by a matrix in abovementioned matrix equation.

Computation of internal friction has not got any well-defined solution with computing methods [2].

As physical origin of damping is different, dynamic computation of systems considers for complex damping, but in order to facilitate calculations all the kinds of damping are reduced to viscous damping, calculated with the help of (3).

The computed relative attenuation factor for oscillations of traction gear is equal to 0,1 (0,07 for traction engine).

To identify computed dynamic models with real objects it is sufficient at the first stage to compare their own frequencies following main forms of oscillation.

It is known that proper frequencies are functions of main parameters of dynamic system which are weight and rigidity. That's why it is reasonable to suppose that if computed and experimental data on own frequencies coincide, then the proposed model doesn't contradict the reality.

To compute proper frequencies of the model the researcher solved a system of matrix equations based on previously mentioned equations (4) and (5).

The calculations were executed with the help of finite elements model, built according to geometrical model (pic.1) within software package «Patran-Nastran».

Pic. 4 and 5 show main forms of oscillation with 50,4 Hz and 63 Hz frequency which are closest to the forms of oscillations actuated during the experiment. The pictures show enlarged deformations of mounting brackets.

The table 1 contains values of computed and experimental data.

As the values in the table prove, experimental and computed values of frequencies differ by 6% at most.

Conclusions. The finite elements model developed by the author can be used to solve dynamic problems.

Key words: locomotive, railway, model, system «bogie frame – traction gear», finite element method, forms of oscillation, amplitude spectrum of accelerations.

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