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DYNAMIC MODEL OF A RAILWAY LIFTING CRANE

Jan Vatulin, Denis Potakhov, Egor Potakhov*, Sergei Orlov

Emperor Alexander I St. Petersburg State Transport University
Moskovsky pr., 9, Saint Petersburg, Russia

*Corresponding author: epotakhov@mail.ru

Abstract
Introduction: Currently, mobile boom cranes equipped with telescopic boom equipment are widely used in construction, loading and unloading, as well as installation. **Purpose of the study**: We aimed to develop a dynamic model for a railway lifting crane, taking into account the interaction of its structural elements with each other and the bearing soil surface in a three-dimensional formulation. **Methods**: In the course of the study, we used Simulation and Motion modules of the SolidWorks software package, Klepikov's non-linearly deformable soil model, and Lagrange's equation of the second kind. **Results**: As a result, we developed a numerical analytical 3D model describing dynamic loading and deformation of the "mobile boom crane – foundation" system in a three-dimensional formulation. The model takes into account the following: the internal bending deformation and the interaction of the mating structural elements of a crane (telescopic sections, telescoping hydraulic cylinders, and outriggers), hoist rope rigidity, grillage (framework of sleepers) influence, elastic and plastic properties of the base platform soil, and action of inertial loads on the structural elements of the lifting crane.

Keywords
Railway lifting crane, crane model, numerical dynamic model.

Introduction

Currently, mobile boom cranes (MBCs) equipped with telescopic boom equipment are widely used in construction, loading and unloading, as well as installation (Aleksandrov, 2000). They came into common use due to their high mobility and lifting capacity, the possibility of operation in confined spaces, considerable lifting height and load/attachment lifting and lowering speed, simplified transportation, etc.

It is a known fact that most lifting crane failures are related to dynamic loads causing heavy wear of contacting elements, breakdown of load-bearing metal structures and components of mechanisms, critical deformations, etc. (Aleksandrov et al., 1986). In MBC operation, crane elements experience dynamic loading from the simultaneous action of various loads caused by inertial forces during the rotation of the rotary platform and load lifting/lowering, a pliable foundation, bending stiffness of boom equipment, clearances between the contacting elements, load swinging on a flexible hoist rope, meteorological factors, etc. It has been established that the dynamics of the telescopic boom equipment of a lifting crane significantly affect the dynamic loads of outriggers (Qian et al., 2017; Shcherbakov et al., 2009; Shelmich, 1996).

The load-bearing capacity and gradient of the foundation significantly affect the stability of a lifting crane when loaded. Thus, MBC operating instructions pay a lot of attention to the operating site (MBC location in relation to the pit depending on the type of soil; permissible specific soil loading at the operating site, site preparation methods).

To determine the exact maximum loading of individual lifting crane components, it is important to consider a lifting machine as a system of inter-related elements with the maximum possible number of constituents, taking into account the maximum possible number of loading factors.

To perform capital or emergency works (emergency damage control on track; replacement, loading, and unloading of structural railway track elements, etc.), railway lifting cranes are used.

The operation of railway lifting cranes is distinguished by the fact that such cranes rest on special elements — a framework of sleepers (grillage) (Petukhov et al., 1985; Muzhichkov et al., 1978), which are installed on the subgrade shoulder when cutting a niche in the subgrade area and part of the ballast section, and reduce the average pressure of the outriggers on the ground.

Dynamic loading from rolling stock as well as exposure to atmospheric precipitation, alternating freezing and thawing, moistening and drying, contamination with particles of goods transported (coal, ore, salts, and other minerals), corrosion, etc. result in layer motion and changes in the railway track substructure and its characteristics.

Changes in the soil structure affect the load-bearing capacity and stability of the soil mass (Ishihara, 1996; Savinov, 1979). Ground motion promotes the development of uneven settlements of structures (Ishihara, 1996; Savinov, 1979) (including railway tracks). As a result, the top layers of the soil mass with the grillage may deform in the direction from the longitudinal axis of the railway track to the subgrade shoulder, thus leading to additional loads on the outriggers, which affects the loading of the lifting machine in general.

Thus, layer motion and changes in the base (foundation) structure and characteristics can have a negative impact on the operation of railway lifting machines mounted on that foundation.

The pliability of the supporting elements, clearances between the sections of the telescopic boom (structural and those formed as a result of wear of the supporting elements and outriggers), bending deformation of the extended telescopic sections and telescoping hydraulic cylinders significantly affect the oscillatory processes with regard to the MBC and load. Oscillations result in the formation of dynamic loading and heavy wear of mating surfaces, as well as increase load swinging and the time of its stabilization, which makes it difficult to ensure accurate load positioning. As a result, the MBC output decreases. This effect is most noticeable in railway cranes during track works performed when taking possession of the line.

We aimed to develop a dynamic model for a railway lifting crane, taking into account the interaction of its structural elements with each other and the bearing soil surface in a three-dimensional formulation.

Subject, tasks, and methods

It is rather difficult to conduct experimental studies when trying to achieve the limiting state in actual MBCs. This is due to significant economic losses, a decrease in the operating life of crane equipment, and high potential site hazards. In this regard, to determine the parameters of dynamic loading on the MBC elements, a numerical experiment seems the most reasonable. Simulation makes it possible to save considerable physical resources, significantly reduce the development time during design, analyze loading on the elements of a lifting machine with no damage to the object of the study or changes in its operating life, and avoid danger to life and health of the machine maintenance personnel, designers, and researchers.

The numerical simulation procedure has two stages: developing a virtual model and conducting a numerical experiment with regard to loading modes. The analytical dynamic model of the MBC system shall adequately reflect the basic physical and mechanical characteristics of the actual boom crane elements.

Simulation is carried out in SolidWorks Simulation (module for structural analysis using the finite element method) and SolidWorks Motion (module for comprehensive dynamic and kinematic structural analysis) (Alyamovsky, 2015; Kurowski, 2017).

The virtual 3D model of a lifting crane of the “MBC – foundation” system is based on the structure of the Sokol 80.01M railway boom crane (Fig. 1). Bogies as well as elements not presented in the model in terms of design (power unit engine, rotation mechanism, hook assembly, automatic coupler, winch hydraulic motor, winch, counterbalance, operator’s cab, etc.) are accounted for by concentrated and distributed masses and forces.

The developed numerical dynamic model of the “MBC – foundation” system in SolidWorks Motion conventionally consists of three levels (Table 1) and can be adjusted according to the following:

– the geometric and mass inertia characteristics of lifting crane elements;

– the correspondence between the reactions of the lifting crane model outriggers with the reactions obtained using methods described by Gokhberg (1988) and Vainson (1989);

– stiffness and strength characteristics of elements, parts, and assemblies of the lifting machine and framework of sleepers;

– the theory of soil mechanics;

– the system of differential equations for free and forced oscillations of the telescopic boom section, load, and frame, with account for foundation pliability.

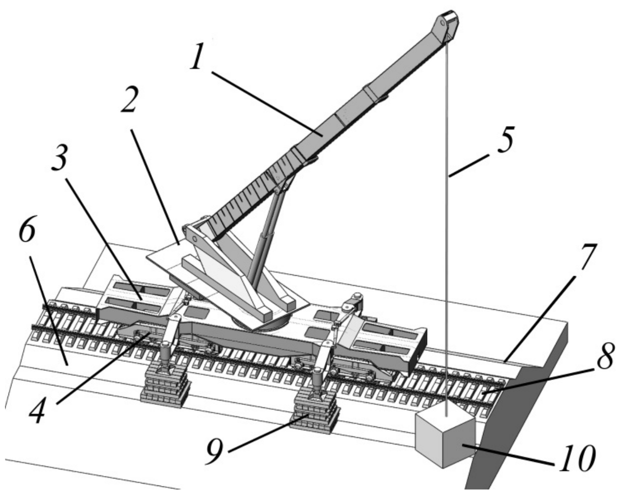


Fig. 1. Numerical dynamic model of the “MBC – foundation” system.
Lifting crane numerical model:
1 — a telescopic boom, 2 — a rotary platform,
3 — a crane platform, 4 — a bogie, 5 — a hoist rope.
Railway track section model: 6 — a ballast section,
7 — a subgrade, 8 — assembled rails and sleepers.
Other elements: 9 — a framework of sleepers, 10 — a load

Due to the fact that, in SolidWorks Motion, elements of mechanical systems are considered rigid, structural deformations are not taken into account. To simulate bending deformation in structures, a “fictitious” joint (Hooke’s joint) is used, which is equipped with viscoelastic elements (springs and a damper) (Fig. 2). The location of the joints is determined based on the results of lifting crane frequency and modal analysis: the “fictitious” joints are placed in the areas corresponding to the instantaneous centers of rotation, speed, and acceleration of the structure: two in the telescopic boom, two in each telescoping hydraulic cylinder (Fig. 2), and one in each outrigger. The parameters of the “fictitious” joint are set in such a way so as to ensure convergence of displacements (deformations) and oscillation modes of the dynamic model in the Motion module with the displacements in the Simulation static strength analysis and oscillation modes in the Simulation modal analysis.

The numerical model of the framework of sleepers consists of two elements connected with a spherical joint. One of the elements is in contact with soil, and the other element has two Kelvin–Voigt models in two planes where the parameters of these models correspond to the pliability of the framework of sleepers.

A nonlinearly deformable model developed by Klepikov (1996), taking into account purely elastic and residual (plastic) deformations, is used as a mathematical model of soil in the “MBC – foundation” numerical system for foundation simulation.

Klepikov (1996) suggested an equation for general determination of the case of non-homogeneous foundation represented by any analytical model:

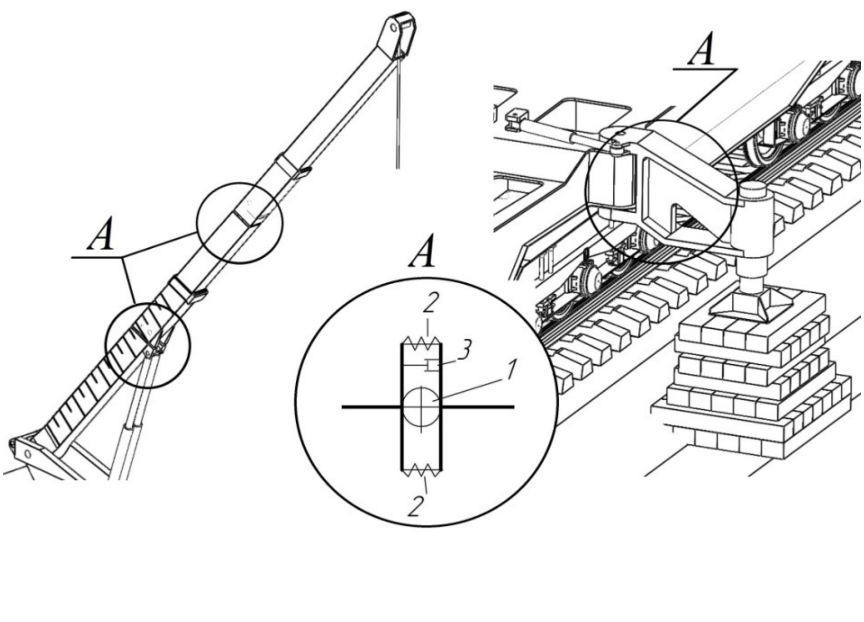
$$s = \frac{\bar{s}(1 - \bar{p}/p_u)p}{\bar{p}(1 - p/p_u)},$$

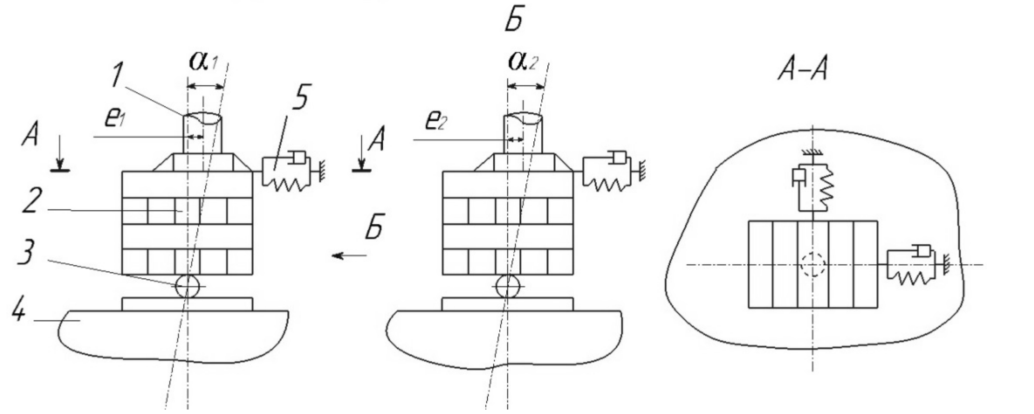
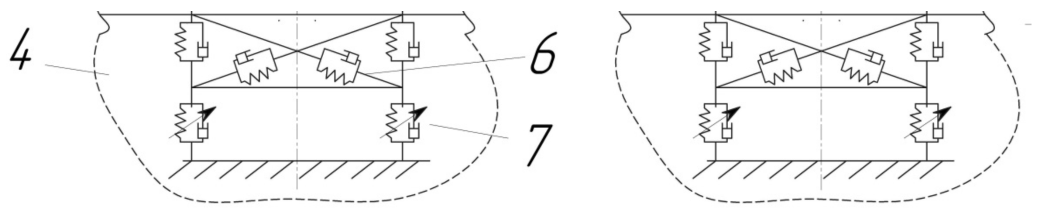
where $\bar{s}$ — the foundation surface settlement at pressure $\bar{p}$ under the foundation bottom, not exceeding the design resistance R of subgrade soil; p — the average pressure uniformly distributed on the foundation surface; P_u — the ultimate pressure on the foundation, corresponding to the exhaustion of its load-bearing capacity.

The settlement $\bar{s}$ is determined considering the shape of the foundation bottom, availability of heterogeneous soil layers, and depth of the compressed foundation.

The rheological model of soil consists of vertical, inclined, and special Kelvin–Voigt models. The horizontal components of the Kelvin–Voigt models simulate shear resistance. The vertical components of the Kelvin–Voigt models simulate the elastic properties of the soil foundation. The special Kelvin–Voigt models were developed to simulate the plastic properties of soil base since they do not feature recovery of deformations after load removal. The parameters of the given elements in the numerical rheological model of soil are adjusted according to Klepikov (1996).

Table 1. Levels of the numerical dynamic model

Level	Analytical model
I	Lifting crane  A — “fictitious” joints: 1 — a spherical joint, 2 — a spring, 3 — a damper

II	Framework of sleepers  1 — an outrigger; 2 — a framework of sleepers; 3 — a spherical joint; 4 — soil; 5 — Kelvin–Voigt models
III	Rheological model of soil  4 — soil; 6 — Kelvin-Voigt models; 7 — special Kelvin-Voigt models

During the analysis of dynamic processes, multi-mass systems of a real-life object with a large number of degrees of freedom are usually reduced to simplified dynamic models (analytical models) that consist of several concentrated reduced masses interconnected by viscoelastic links (springs and a damper) (Gokhberg, 1988; Vainson, 1989; Yablonsky and Noreyko, 2003). The motion of dynamic mathematical models is described by systems of differential equations. Based on their solution, conclusions are drawn about the loads acting on the elements of the object under consideration, as well as the motion of those elements.

Since the motion of the MBC elements is of a spatial nature, the analytical mathematical model of the “MBC – foundation” system is represented in the form of a system of equations where the first subsystem of equations describes the motion of the object under consideration in the vertical plane and the second subsystem of equations describes the motion of the object under consideration in the horizontal plane.

Two separate multi-mass dynamic models of the MBC elements are formed: horizontal and vertical models, including masses of the load, middle and upper sections, piston and rod of the upper telescoping hydraulic cylinder, piston and rod of the lower telescoping hydraulic cylinder, frame, outriggers, and frameworks of sleepers. The reduced masses are connected by viscoelastic links (Kelvin–Voigt models). The frameworks of sleepers and the foundation are also connected with viscoelastic elements. Two separate subsystems of differential equations, based on Lagrange’s equation of the second kind, are composed: the first one describes the motion of the load and MBC elements in the vertical plane, and the second one describes the motion of the load and MBC elements in the horizontal plane. The equations include the kinetic and potential energies of the system as well as the Rayleigh dissipation function.

The general solution of the system of differential equations is based on the sum of the general integral of the corresponding system of homogeneous equations and the particular integral of the analyzed non-homogeneous system. The first solution describes free oscillations of the object under consideration, and the second solution describes forced oscillations of the object under consideration (Yablonsky and Noreyko, 2003).

Results and discussion

As a result of the studies, we have developed an analytical 3D model describing dynamic loading and deformation of the “MBC – foundation” system in a three-dimensional formulation. The model takes into account the following: the internal bending deformation and the interaction of the mating structural elements of a crane (telescopic sections, telescoping hydraulic cylinders, and outriggers), hoist rope rigidity, grillage (framework of sleepers) influence, elastic and plastic properties of the base platform soil, and action of inertial loads on the

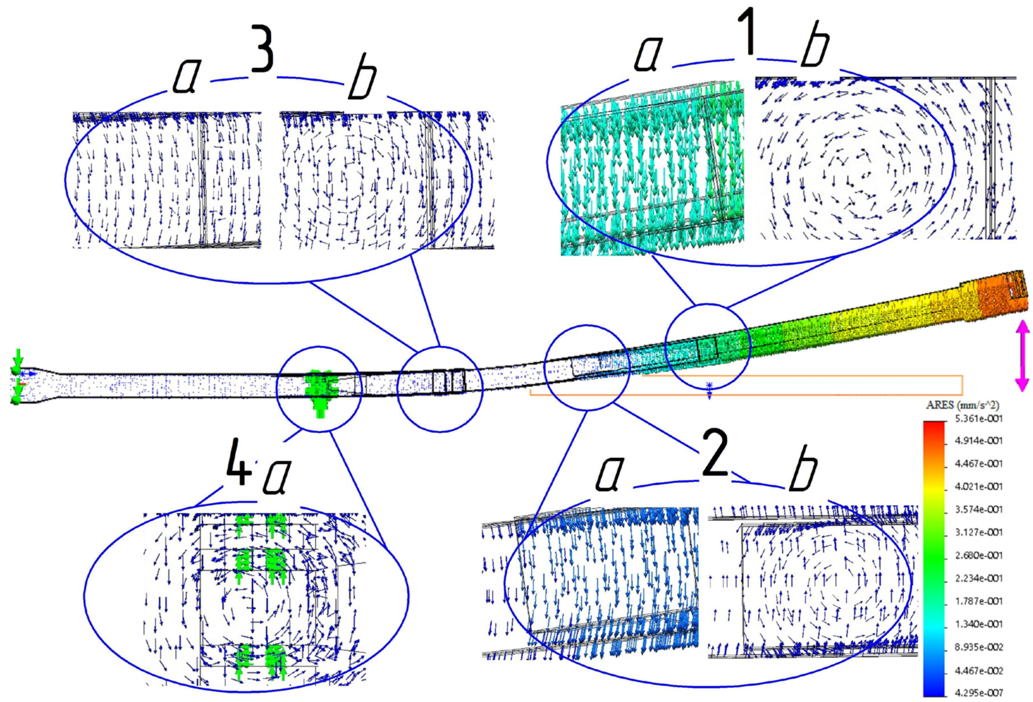


Fig. 2. Vector representation of the acceleration of oscillatory processes in the telescopic boom in the horizontal plane: 1, 2, 3, 4 — areas of instantaneous centers of rotation, speed, and acceleration; a — the basis vector; b — the short-term vector

structural elements of the lifting crane.

Conclusions

Currently, mobile boom cranes equipped with telescopic boom equipment are widely used in construction, loading and unloading, as well as installation. It is a known fact that most lifting machine failures are related to dynamic loads. It is rather difficult to conduct experimental studies when trying to achieve the limiting state in actual lifting cranes. This is due to significant economic losses, a decrease in the operating life of crane equipment, and high potential site hazards. In this regard, to determine the parameters of dynamic loading on the MBC elements, we have performed a numerical simulation in SolidWorks Simulation and SolidWorks Motion.

As a result of the studies, we have developed a numerical analytical 3D model describing dynamic loading and deformation of the “MBC – foundation” system in a three-dimensional formulation. The model takes into account the following: the internal bending deformation and the interaction of the mating structural elements of a crane (telescopic sections, telescoping hydraulic cylinders, and outriggers), hoist rope rigidity, grillage (framework of sleepers) influence, elastic and plastic properties of the base platform soil, and action of inertial loads on the structural elements of the lifting crane. The developed analytical spatial model makes it possible to obtain temporal dependencies for the kinematic and dynamic parameters of the lifting crane elements, counter-forces (reaction forces) of the mating components of the system in the dynamic loading mode during lifting machine operation on a pliable foundation. It seems possible to determine the nature of loading in any arbitrary point (or a set of points) of the analytical model, considering the mutual influence of the bending deformation of the crane elements and the rigidity of the platform.

The concept of analytical spatial model development can be extrapolated to all types of lifting machines with any type of foundation.

The results of the studies will improve the accuracy of simulating lifting crane operation and crane elements loading, which, in turn, will improve lifting machines’ operational safety. Besides, it is possible to upgrade the developed mathematical model: by adding new or replacing existing structural and “fictitious” elements (viscoelastic elements, joints, sections, load, outriggers, etc.); by adding various types of external loads; by changing the position and motion modes of the elements; and by applying control systems and optimization methods.

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ДИНАМИЧЕСКАЯ МОДЕЛЬ ЖЕЛЕЗНОДОРОЖНОГО ГРУЗОПОДЪЕМНОГО КРАНА

Ян Семенович Ватулин, Денис Александрович Потахов, Егор Александрович Потахов*, Сергей Васильевич Орлов

Петербургский государственный университет путей сообщения Императора Александра I
Московский пр., 9, Санкт-Петербург, Россия

*E-mail: epotakhov@mail.ru

Аннотация
В настоящее время для выполнения различных строительных, погрузо-разгрузочных и монтажных работ широкое используются самоходные стреловые краны, оснащенные телескопическим стреловым оборудованием. **Цель исследования:** Разработка динамической модели железнодорожного грузоподъемного крана с учетом взаимодействия конструктивных элементов крана между собой и с грунтовой опорной поверхностью в трехмерной постановке. **Методы:** Модули Simulation и Motion программного комплекса SolidWorks, нелинейно-деформируемая модель грунта С.Н. Клепикова, уравнение Лагранжа второго рода. **Результаты:** Разработана численная расчетная 3D-модель, которая отражает динамическое нагружение и деформирование системы «стреловой самоходный кран – основание» в трехмерной постановке, учитывая: собственную изгибную деформацию и взаимодействие сопряженных конструктивных элементов крана (телескопические секции, гидроцилиндры телескопирования, аутригеры), жесткость грузового каната, влияние шпальной клети, пластические и упругие свойства грунта опорной площадки, действие инерционных нагрузок на элементы и узлы грузоподъемного крана.

Ключевые слова
Железнодорожный грузоподъемный кран, модель крана, численная динамическая модель.