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Original Research Article

Dynamic responses of a gantry crane system due to a moving body considered as moving oscillator

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ABSTRACT

This paper discusses a combined finite element and analytical method for obtaining transverse and longitudinal vibrations of a gantry crane system subjected to an elastically suspended moving body. The two-dimensional inertial effects of the moving body are included in derivation of differential equation of motion for the system. Factors as speed, acceleration and suspension characteristics of a moving body are studied, including the influence of structural damping. The obtained results validate the presented approach and can be used in the design process of gantry cranes.

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1. Introduction

Nowadays, we have a permanent tendency towards constant improvement of performances of machines and systems in general, including their increase in size. High-performance large size material handling and conveying machines, such as e.g. container cranes, huge gantry cranes, ship unloaders and ship loaders, etc., as well as construction and surface mining machines, such as e.g. bucket wheel excavators, spreaders, reclaimers, stacker feeding bridges etc., have found an extremely wide application in almost all areas of human activities [1]. Very different technological requirements and working conditions resulted in a large variety of their support structures (with changeable or unchangeable working geometry), trolleys and suspension systems, working devices and accordingly their kinematics and dynamics. However, regardless of the differences, almost all considered machines from this class of equipment are exposed to the effects of a working load whose basic characteristic is the changeability of intensity and/or position relative to the support structure of the machine [1]. The expressed facts point to the exceptional significance of identifying their behaviour under dynamic loads, as well as response of the considered machines or their subsystems, as an extremely important stage in their design, particularly having in mind that the improvement of performances is not adequately followed by methods of calculation in many cases [2]. Also, a thorough and sophisticated identification of dynamic behaviour creates a basis for avoiding failures, damages and serious accidents that inevitably lead to very high financial losses and presents at the same time a potential serious risk to the workers' safety

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and life. For instance dynamic and vibration analysis, done for different purpose, of some already mentioned type of equipment is shown in [3–8]. Also, good awareness of dynamic characteristics is necessary to reduce vibrations of the machine and, subsequently, to increase durability of the structure while the fatigue will be reduced [9,10].

Dynamic behaviour of high performance machine (HPM) depends on relatively numerous factors and an analysis of dynamic behaviour demands to solve previously, in a suitable manner, the following two problems [11]:

- How to create dynamic model of the machinery;
- How to create model of the external load.

1.1. *Moving load problem in structural dynamics of cranes*

The progress of the material handling industry has been remarkable in many ways. Considering the enormous capital costs, one of the most remarkable changes has been in the size of equipment and facilities. Over time, cranes' sizes and lifting capacities have increased. While the size, mass and strength of the crane structure have also increased, the stiffness of the crane structure has not been increased proportionally. That means the crane response to the trolley motion has changed and can cause unwanted crane deflections in the vertical plane. Increased trolley and hoist speeds are obvious targets for increased productivity [12]. The dynamic behaviour of a high-performance crane structure is different than that of a smaller crane. Vibrations are a serious problem in crane systems that are required to perform precise motion in the presence of structural flexibility. In practice it is very difficult and expensive to do experimental research on a real-size high-performance crane or even on a scale-model. For this reason investigations on mathematical models are a necessity, especially during the design stage.

Generally, dynamics of lifting machines consist of structural dynamics and suspended load dynamics [13] and focused on different problems of vibrations due to external excitations, such as for instance trolley motion [14], wind gusts [15] and slewing motion effects [16].

The moving load problem is one of the fundamental problems in structural dynamics. A lot of work has been reported dealing with the dynamic response of structures in the field of transportation and various constructions such as are cranes, under the influence of moving loads. The application of moving load problem in cranes dynamics has obtained special attention in the engineering researches in the last few years, but unfortunately not too much literature on the subject is available. The paper [17] is according to the authors' best knowledge the first attempt to increase the understanding of the dynamics of cranes due to the moving load. Also, the moving load problem for mega container cranes is considered in [12,18].

The basic approaches in trolley modelling are: the moving force model; the moving mass model and the trolley suspension model or so-called moving oscillator model. A detailed comparison in structural dynamics of cranes between the moving force model and the moving mass model is given in [19] and an appropriate way of modelling is recommended. Moving mass approach is needed, [20], because it gives more accurate results for dynamic responses than moving force approach.

The trolley suspension models represent physical reality of the system more closely, because, often, the vehicle mass is suspended by means of springs and dampers in such models – moving oscillator problem. This happens for some specific constructions of gantry cranes and unloading bridges, mostly used for bulk materials handling. However, moving oscillator problem is not considered up to now in structural dynamics of high-performance machines, except for the case of a standard bridge crane as shown in [21].

2. Model formulation

The general approach in moving load problems at cranes is also used here, thus the system of the gantry crane (Fig. 1a) is divided into two parts: the framework (structure) and the moving system. The framework is a 2D discrete model consisted of top beam with length L, pier leg with height H and sheer leg with height h. The discretization of the framework (Fig. 1b) is done by using FEM, with plane-frame elements [22]. The top beam is divided in 10 identical elements and each leg by 2 elements. This *low* number discretization is usual in finite element formulation at moving load problems [25]. This is in relation with computational procedures that follow this approach due to the fact that large number of DOF's would additionally increase CPU time for obtaining solutions with direct integration method. Hence, framework has 41 DOF's (with extraction of the restrained displacements from supports) forming the structure displacement vector $\mathbf{U}$.

The moving system (Fig. 1c) with total mass m_{ss} is consisted of the mass of trolley, m_1, and mass of hoist with payload, m_{23}, connected with linear spring with stiffness k. It is assumed that mass m_1 is always in contact with the top beam. The additional DOF of the moving oscillator is vertical displacement of the mass m_{23}, denoted as y (Fig. 2c). The global position of the moving system on the top beam is assumed known and defined by coordinate $x_m(t)$ (Fig. 2b). Here, the acceleration/deceleration is also included in calculation because of the trolley trapezoidal speed pattern. It is assumed, by model of the gantry crane system, that a loading is symmetrically distributed on the top beam rail(s) and furthermore that relationship between the framework and the moving system can be simplified into one moving load $P(t)$, with projections in two-dimensional directions $P_x(t)$ and $P_y(t)$ (Fig. 2b).

3. Structural property matrices

The equation of motion for a framework (structural system) is represented as follows

$$\mathbf{M}_{st}\ddot{\mathbf{U}} + \mathbf{C}_{st}\dot{\mathbf{U}} + \mathbf{K}_{st}\mathbf{U} = \mathbf{P}(t) \quad (1)$$

where $\mathbf{M}_{st}$, $\mathbf{C}_{st}$, $\mathbf{K}_{st}$ are the mass, damping and stiffness matrices of the structural system; $\ddot{\mathbf{U}}$, $\dot{\mathbf{U}}$, $\mathbf{U}$ are the respective acceleration, velocity and displacement vectors for the system and $\mathbf{P}(t)$ is the external force vector acting upon the structure.

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