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Dynamics of container cranes: three-dimensional modeling, full-scale experiments, and identification

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ABSTRACT

A three-dimensional modeling of container cranes subject to wind loads is presented together with full-scale experimental tests, system identification and model validation. The container is modeled as a rigid body elastically suspended from the trolley running along rails on top of the crane boom and the girder. Differences are discussed with respect to a constrained model, in which the cables are unstretchable. Experimental investigations are carried out on a full-scale container crane and the modal characteristics together with the damping coefficient are identified as a function of the container height. Moreover, the nonlinearities induced by large-amplitude oscillations involving some of the modes are highlighted both in the context of numerical simulations and experimental tests. Time integration is carried out to validate the mechanical model by comparing its predictions with the experimental results. Typical working maneuvers together with the effects of wind-induced loads are taken into account to study the three-dimensional crane response.

1. Introduction

Container cranes are formidable machines typically employed in port transhipment hubs for cargo movement whose efficiency, directly linked to the crane effective speed, strongly influences the productivity of the overall terminal. To optimize the crane performance in terms of minimization of the working operation time, the accurate characterization of the dynamic response of containers during the lifting/lowering maneuvering phase is an essential requirement. Moreover, harbors are often located in windy areas, characterized by the occurrence of gust fronts that can affect the cranes working efficiency and, sometimes, compromise the safety of workers. Hence, the effects of wind loads on container dynamics need to be taken into account. As shown in Fig. 1, container cranes consist of a railway-driven steel-frame tower sustaining at its top a boom and a girder whose length can vary across the quay. A manually-controlled trolley can move along rails located on the crane boom and maneuver the payload (the container) in and out of the docked ships by a system of hoisting cables and pulleys, directly connected to a spreader bar, positioned atop the container.

In the literature, several studies on container cranes dynamics are available and different modeling approaches (e.g., planar or three-dimensional models with elastic/rigid hoisting cables) are proposed to investigate their behavior. A comprehensive classification of these models is given in [1] where applications and limitations of the different theories are discussed.

The dynamic behavior of the lightly damped container crane system can be complex and can feature three-dimensional (3D) container motions, involving also the yaw component when excited by wind loads. Other excitation scenarios can be represented by badly executed maneuvers, which can give rise to in- and out-of-plane large-amplitude pendular motions. Therefore, the analytical modeling often adopted in the literature, based on the planar motion assumption, may turn out to be inadequate to describe the truly 3D dynamics of container cranes. Moreover, due to light damping, autoparametric resonances between different modes may arise thus causing loss of stability of planar pendulation motions into more complex 3D motions. Hence, large-amplitude oscillations of the payload must quickly decay before further working operations can take place, since this situation may result in damages to the crane structure itself or in a hazard to the environment.

In order to investigate the dynamic behavior of container cranes, in recent years several models have been developed and control strategies have been proposed to overcome the potential issues arising from uncontrolled large-amplitude oscillations. Studies of

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Fig. 1. The quayside container crane at the Cagliari International Container Terminal (CICT) in Cagliari (Sardinia, Italy).

container crane pendulations were first conducted in [2] where the dynamic behavior of simply suspended objects was investigated and an extensive review of the theory was presented. In the same work, a control strategy, based on programmed acceleration/deceleration phases of the trolley motion, was proposed and numerical results were compared with experiments performed on a scale model.

Payload oscillations may also be excited, as in ship-mounted cranes, from the sea wave motion that can induce oscillations of the ship and, consequently, of the suspended container. Wave-induced oscillations were described in [3] where the planar motion of a one-degree-of-freedom (1-dof) container crane model was studied and a delayed position feedback controller was proposed. Available experimental data were also reported to validate the numerical results.

One-dof pendulum models, largely employed in the literature, are not appropriate to describe the complex dynamics of a container–crane system and to capture the geometric nonlinearities affecting the container motion and arising from the hoisting system. A more refined planar model was proposed in [4,5] where a double pendulum, two-dimensional (2D) model was proposed and fully nonlinear equations of motion were provided in Cartesian coordinates. Planar pendulum-type crane models were also employed to study payload oscillations control via a nonclassical vibration absorber in [6], via an active open-loop methodology [7] or fuzzy controls using a variable truss geometry [8].

In [9] the problem of geometrical extension was addressed for widely spaced cable reeving configurations in container cranes, a phenomenon giving rise to unevenly distributed cable stretch and uneven tensions. A theoretical study of the kinematics of a typical multi-cable suspension system was proposed in [10] where the complete analytical derivation in terms of all translational and/or rotational displacement components was shown. In [11] the same authors illustrated the steps necessary to model the dynamics of a rubber-tyred gantry crane and discussed various modeling criteria by placing the emphasis on the importance of nonlinear coupling between the chosen coordinates. A 3D model of suspended containers was developed in [12] where the motion of the container was described accounting for the deformability of the hoisting cables and for disturbances like side winds and unbalances in the center of gravity of the container although no details were provided on the modeling of the wind excitation.

Numerical simulations, aimed to study the effects of nonlinearities arising from mechanical friction and air resistance, were performed in [13] where the results were also experimentally validated. In [14,15], modeling of a variety of pendular structures (such as gantry cranes) was proposed and suitable control strategies were thoroughly examined by highlighting the computational implications of the models on the control implementations. A 1/10 laboratory scale model of a gantry crane was employed in [14] to test the performance of a feedback linearized control method, whereas in [15] single- and multi-cable models of gantry cranes were discussed.

The dynamics of the crane structure (i.e., the supporting frame and boom) should be taken into account when the flexibility of the boom has the potential to affect the payload oscillations or when seismic excitations cannot be neglected. In [16] the dynamic behavior of gantry cranes was investigated taking into account also the flexibility of the crane structure, and in [17] a six-dof analytical model was developed to investigate the behavior of container cranes under seismic excitation. Numerical results were validated through experiments on a scale model. A finite element (FE) model of a quayside crane was implemented in [18] to study the dynamics of a crane and to identify its modal properties showing that, for particular crane configurations, the analysis of container oscillations should take into account the deformability of the boom. Wind-induced oscillations of container cranes were investigated in [19] by means of wind tunnel tests performed on a 1/150 scale model. In the experiments, the wind environment nearby the container crane located in a port was simulated by assuming a uniform flow condition and considering different wind directions.

In the present work, a six-dof model describing the dynamics of container cranes is presented. The fully nonlinear equations of motions, accounting for the trolley-induced motion and the hoisting cables length variation (associated with typical working maneuvers) and the wind-induced excitation, are obtained via the Euler–Lagrange equations [20]. The dynamic behavior of container cranes involving out-of-plane modes excited by eccentric loading and initial conditions is investigated in depth. Full-scale experiments are carried out on a container crane in the Port of Cagliari first to identify the main system parameters, such as the overall crane damping, and further to validate the theoretical/numerical predictions in terms of linear and nonlinear features.

2. Nonlinear parametric modeling

The approach proposed in this work neglects the interaction between the crane supporting structure and the suspended container. Hence, the container motion is influenced only by the elasto-geometric characteristics of the hoisting cables, their geometry and the container size. This type of modeling is justified by the fact that the boom frequencies are much higher than the payload (container) frequencies. This typically occurs for most of the container–crane configurations. The possibility of nonlinear interactions between the container and the boom oscillations may exist for very special conditions.

As shown in Fig. 1, quayside cranes are structures composed by vertical frames, that can move on straight rails along a prescribed direction, having on their top a truss girder that can move relative to the frames and vary the length of its cantilevered part supporting the trolley from which the container is suspended. The length of the boom, the payload mass (container), and its position along the boom govern the dynamic behavior of the truss girder in the vertical plane. Due to its geometric characteristics, the truss girder shows negligible deformations in the horizontal plane. However, its deformability in the vertical plane is higher although its frequencies are well separated from the frequencies of the pendular modes of the container.

In the next sections, the nonlinear equations governing the dynamics of containers subject to wind-induced excitations are obtained. The container is modeled as a rigid body elastically