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ScienceDirect

Procedia Engineering 199 (2017) 501–509

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

Payload oscillations control in harbor cranes via semi-active vibration absorbers: modeling, simulations and experimental results

Andrea Arena[a,*], Walter Lacarbonara[a], Arnaldo Casalotti[b]

[a] *Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy*
[b] *Department of Mechanical and Industrial Engineering, University of Roma Tre, Via della Vasca Navale 81, 00146 Rome, Italy*

Abstract

Semi-active vibration absorbers (SAVAs) are proposed to suppress large amplitude oscillations in container cranes during maneuvers and wind forcing. The SAVA design and optimization are achieved via suitable nonlinear models, numerical simulations, and laboratory as well as full-scale tests. A comprehensive nonlinear modelling, featuring a full three-dimensional crane model and the adaptive vibration control architecture, is devised. The container is modeled as a rigid body elastically suspended from the trolley traveling along the crane boom. Two identical SAVAs are studied coupling their equations of motion - which include the impact against rubberized end stops - with the container crane dynamics. Suitable parametric analyses are carried out to investigate and optimize the control devices. Full-scale experiments are performed to validate the semi-active control architecture which proves to be a feasible approach.

Peer-review under responsibility of the organizing committee of EURODYN 2017.

Keywords: Container cranes, Vibration absorbers, Semi-active control, Wind loads, Full-scale experiments

1. Introduction

The productivity in port transhipment hubs has always been linked to the efficiency of container cranes. These are huge machines adopted for cargo movement which have to provide high precision during containers maneuvering in the lowest possible time. Moreover, the presence of strong, gusty winds in harbors can affect the cranes efficiency through a drastic increment of collisions and can further compromise the safety of workers. In most of the port transhipment hubs the performance of such machines relies on the ability of the operators to control the containers oscillations while maximizing the maneuvering speed.

Typical active control strategies adopted to mitigate unwanted payload oscillations are either based on trolley motion control or on the hoisting cables length variations [1–4]. However, active controllers tend to be switched off by the crane operators since the controllers interact with the maneuver commands dictated by them thus making the operators direct control more difficult. This is why passive or semi-active devices, not interfering with the operators effected commands, are here investigated. Because the frequency of the pendular motion of the container varies during

* Andrea Arena. Tel.: +39-06-44585885.
E-mail address: andrea.arena@uniroma1.it

1877-7058
Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.136

the typical working maneuvers, semi-active vibration absorbers are designed to change their stiffness and damping so as to ensure maximum energy transfer.

There is a wide literature on container cranes dynamic models [5–8]. The authors of this work proposed a 3D model accounting both for the elasticity of the variable-length hoisting cables and the deformability of the crane boom [9–11]. Such full 3D model which incorporates the boom elasticity highlighted the likelihood of parametric interactions between the dynamics of the boom and the container pendular motions [11]. The here employed model accounts only for the elasticity of the four hoisting cables and the 3D rigid-body dynamics of the container. Moreover, the finite stroke of the SAVAs coupled with the container dynamics motivated the study of their impacts with rubberized stops modeled as visco-elastic barriers.

The effectiveness of the proposed control system is first investigated via parametric numerical simulations showing the better performance of the semi-active system compared to that of passive absorbers. Full-scale experiments carried out in the port of Cagliari proved the feasibility of the control strategy.

2. Problem formulation

The modeling approach proposed to study the effects of the control action neglects the interaction between the crane structure elasticity and the suspended container. The container motion is influenced by the hoisting cables characteristics and the container size. As shown in Fig. 1, quayside cranes are steel structures made of movable vertical frames supporting on their top a truss girder on which the trolley, driven by an operator, can travel across the boom. Moreover, the operator commands the length of the hoisting cables.

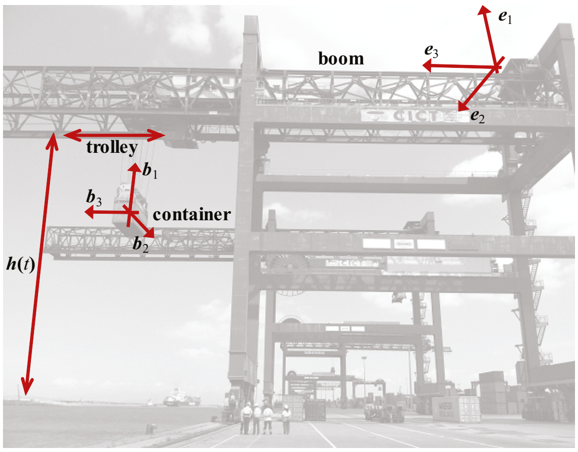

Fig. 1: The QC-7 container crane at the Cagliari International Container Terminal (CICT), Cagliari, Sardinia, Italy.

By considering in Fig. 1 the fixed Cartesian frame $(\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3)$ and two body-fixed moving frames having their origin in the center of the trolley and in the container center of mass, respectively, generalized coordinates are introduced to describe the position and rotation of the container. In consonance with [10], the current configuration of the container-crane system is described by the position vector $\boldsymbol{p}(t)$ of the container center of mass and the vector $\boldsymbol{q}(t)$ that gives the position of the trolley center of mass. The finite rotations of the container-fixed frame are parameterized by the sequences of rotation angles $(\phi_1(t), \phi_2(t), \phi_3(t))$. The six generalized coordinates are then listed in the vector $\boldsymbol{\xi}(t) = (p_1(t), p_2(t), p_3(t), \phi_1(t), \phi_2(t), \phi_3(t))$.

To obtain the equations of motion governing the dynamics of the container-crane system, the Lagrangian L of the system is computed as $L = K - V - W_c$ where V and K denote the potential and kinetic energies of the container, and W_c is the cables stored energy. Thereafter, the six equations of motion are derived according to the Euler-Lagrange equations

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\xi}_k}\right) - \frac{\partial L}{\partial \xi_k} + d_k \dot{\xi}_k = F_k\,, \quad k = 1, \ldots, 6\,, \tag{1}$$