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Vertical dynamics of a single-span beam subjected to moving mass-suspended payload system with variable speeds

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ABSTRACT

This paper presents the vertical dynamics of a simply supported Euler–Bernoulli beam subjected to a moving mass-suspended payload system of variable velocities. A planar theoretical model of the moving mass-suspended payload system of variable speeds is developed based on several assumptions: the rope is massless and rigid, and its length keeps constant; the stiffness of the gantry beam is much greater than the supporting beam, and the gantry beam can be treated as a mass particle traveling along the supporting beam; the supporting beam is assumed as a simply supported Bernoulli-Euler beam. The model can be degenerated to consider two classical cases—the moving mass case and the moving payload case. The proposed model is verified using both numerical and experimental methods. To further investigate the effect of possible influential factors, numerical examples are conducted covering a range of parameters, such as variable speeds (acceleration or deceleration), mass ratios of the payload to the total moving load, and the pendulum lengths. The effect of beam flexibility on swing response of the payload is also investigated. It is shown that the effect of a variable speed is significant for the deflections of the beam. The accelerating movement tends to induce larger beam deflections, while the decelerating movement smaller ones. For accelerating or decelerating movements, the moving mass model may underestimate the deflections of the beam compared with the presented model; while for uniform motion, both the moving mass model and the moving mass-payload model lead to same beam responses. Furthermore, it is observed that the swing response of the payload is not sensitive to the stiffness of the beam for operational cases of a moving crane, thus a simple moving payload model can be employed in the swing control of the payload.

1. Introduction

The creation of overhead cranes greatly facilitates the efficiency of transportation and liberates the labor forces. The traditional overhead cranes are widely used for transportation in manufacturing factories, harbors/ports, freight warehouses, and etc. But right now in China, they are increasingly used in overhead train depots and buildings due to the limitation of land resources, especially in urban cities. The whole structures of the overhead train depots or overhead buildings usually consist of two parts—the upper buildings and the lower space, divided by a thick concrete or steel-concrete composite platform. The upper buildings, located on the platform, are usually used as management offices or for living uses. While the lower space,

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Nomenclature

a	acceleration (or deceleration) of the trolley
E	Young's modulus
I	inertia moment of the beam section
l	length of the pendulum
L	Lagrangian
n	ratio of the length of the pendulum to the length of the beam
N	truncated mode number of the beam
t	time
T	system kinetic energy
U	system potential energy
α	ratio of the payload mass to the total moving mass
θ	pendulum angle from the vertical
μ	ratio of the total moving mass (summation of trolley and payload masses) to the first modal mass of the beam
Ω	natural frequency of the pendulum payload
F_p	excitation force of the rope induced by payload
F_{pv}	vertical component of F_p
l_b	length of the beam
l_c	critical length of the rope when resonance occurs
m_b	mass of the beam per unit length
m_p	mass of the payload
M_t	mass of the trolley
v_0	initial velocity of the trolley
x_b	coordinate of the beam in the $\mathbf{i}$ direction
x_t	coordinate of the trolley in the $\mathbf{i}$ direction
x_p	coordinate of the payload in the $\mathbf{i}$ direction
y_b	coordinate of the beam in the $\mathbf{j}$ direction
y_t	coordinate of the trolley in the $\mathbf{j}$ direction
y_p	coordinate of the payload in the $\mathbf{j}$ direction
ω_i	ith natural frequency of the beam
$\mathbf{i}, \mathbf{j}, \mathbf{k}$	basis vectors of the dextral inertial frame
$\mathbf{r_b}$	position vector of the beam in the dextral inertial frame
$\mathbf{r_t}$	position vector of the trolley in the dextral inertial frame
$\mathbf{r_p}$	position vector of the payload in the dextral inertial frame
$q_i(t)$	*i*th generalized coordinates of the beam
$\varphi_i(x)$	*i*th mode shape of the beam
$\dot{()}$	time derivative
$(\ )'$	spatial derivative

equipped with overhead cranes, is used for transportation purpose. Due to its special structural type, relatively heavy transportation mass, and high operating frequency, the annoying vibration of the upper buildings under crane loading is usually complained by occupants [1]. As the basis of the moving overhead crane vibration problem, this paper pays special focus on vertical dynamics of a simply supported beam subjected to a moving overhead crane with suspension payload.

During the past five decades, extensive researchers have mounted their interest in modeling and control of cranes [2–8]. A comprehensive review about these studies could be found in Refs. [2,3], for both gantry cranes, rotary cranes and boom cranes. This paper mainly focuses on overhead cranes (gantry cranes). Generally, there are two approaches for modeling of overhead cranes, based on different assumption of the hoisting lines: the lumped mass model [4] and the distributed mass model [5]. For a distributed mass model, the hoisting line is modeled as a distributed-mass cable and the payload and hook are treated as a point mass, while for the lumped mass model, the hoisting line is treated as a massless link. Massive profound work has been done on the suppression of the sway motion or trajectory planning of the payload [2–8], but these are not the focus of this study and will not be discussed in detail in this paper. It should be noted that all these studies only concern the modeling of cranes, the contribution of beam flexibility is not included in their modeling.

The problem described herein of a single-span beam subjected to a moving mass with suspended payload could be basically treated as a moving mass problem. The main challenge arises due to the adding of the swing degree of freedom (DOF) of the pendulum payload, which adds more coupling effects and thus results in difficulties in solving the problem. A lot of profound works could be found in the literature dealing with the moving mass problems [8–17]. The pioneer work is