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Optimal velocity profile for a cable car passing over a support

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ABSTRACT

In this paper, we present a theoretical model that solves the problem of minimization of aerial ropeway vehicle oscillations that are induced as the vehicle passes over a support. The task is formulated as an inverse problem, where the vehicle oscillations are minimized by an appropriate choice of the velocity profile of the hauling cable. We study two general cases numerically, a single vehicle system (FUNIFOR), as well as a classical aerial ropeway with two vehicles. In both cases we find optimal velocity profiles that show a considerable improvement of the oscillatory behavior of the vehicles as compared to constant velocity profiles and optimal profiles that have been obtained analytically by loosening some of the constraints for the system. In addition to a minimization of the vehicle oscillations, we also optimize the time that elapses as the vehicle is hauled through the system. We believe that this exploratory study lays a sound basis for various possible future studies and practical applications (Computer Aided Engineering).

1. Introduction

Optimization of physical processes or mechanical systems is an active and broad field of research, ranging from nano–structured systems to large constructions like buildings or cable rope ways (Wenin et al., 2010; Thaler et al., 2016; Banichuk et al., 2013). In this paper we apply numerical minimization methods to optimize the oscillatory behavior of cable ropeway vehicles induced by the vehicle passing over a support. Since the vehicles of state–of–the–art ropeways travel at speeds of up to 15 m/s, the minimization of vehicle oscillations induced by large deflection angles in the support geometry are an important and essential task. In this study we use the time–dependent velocity profile of the vehicle as a free variable to design an optimal support crossing with minimal induced vehicle oscillations (real world cable car systems use time-dependent velocity profiles for the hauling cable to control vehicle oscillations). We consider two cases, a single vehicle, as well as two vehicles coupled through a hauling cable with a common velocity.

The computation of the "exact" dynamics of a vehicle is a complicated task, since a coupled system of the time–dependently driven hauling cable, the support cable, the hauling cable suspensions on the support cable, the counterweight and one or two vehicles, as well as several damping devices have to be taken into account (Brownjohn, 1998; Bryja and Knawa, 2011; Knawa and Bryja, 2014; Sofi, 2013; Yi et al., 2017). Wind induced cable- and vehicle oscillations were the subject of various studies, where the wind forces were introduced through a source term in the equations of motion (Kopanakis, 2010; Zhou et al., 2011; Engel and Löscher, 2003; Volmer, 1999; Kang et al., 2013; Hoffmann, 2009). Those studies were formulated as direct problems, that is, the calculation and simulation of the response of a system for given system parameters that have been evolved through dynamical equations.

In this investigation we consider inverse problems: given the dynamical equations, we try to determine optimal system parameters that minimize the vehicle oscillations, while making the run–time as short as possible. The optimization is performed numerically by using the frameworks Mathematica and Matlab (Matlab homepage; Mathematica homepage).

Our model captures the full dynamics of the vehicles, modeled as damped physical pendulums, but neglects the dynamics of the hauling cable, which will be included in a future study. Consequently, the obtained optimal velocity profiles correspond to the velocity at the suspension point of the vehicle (running gear), which, in this simplified case, is equal to the velocity of the hauling cable along the circumference of the driving disk, since the hauling cable is assumed to be rigid.

Furthermore, we assume a simplified time–independent trajectory

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of the vehicle suspension point, that is, we neglect the back–action of the vehicle's motions on the dynamics of the support cable. Accounting for this additional factor would lead to complicated systems of non-linear equations (Brownjohn, 1998; Bryja and Knawa, 2011; Knawa and Bryja, 2014) which lie beyond the scope of this first optimization study. In our approach, we use a set of ordinary differential equations, which can be integrated numerically in a fast, stable and straightforward fashion. In order to use standard global and local optimization strategies we defined a cost function J, which penalizes vehicle oscillations and rewards short run–times. The innovative aspect of our study is, that we provide a novel numerical optimization framework to minimize vehicle oscillations. While the base model presented here assumes a simple support head geometry and neglects the dynamics of the hauling cable, our approach is general enough to accommodate arbitrary geometries for the support head. Including the dynamics of the hauling cable can be achieved by solving for the modified velocity profile of the suspension point for a given velocity profile of the driving disk and by providing a model for the elasticity of the hauling cable. Another advantage of our framework is, that it expresses all quantities (vehicle deviation angles, velocities) in terms of positions, which makes it accessible to experimental observations, which are usually measured with respect to positions.

Our paper is organized as follows: Sect. II contains the geometric description of the vehicle paths in space. In Sect. III, we set up the equations of motion of the system. Sect. IV is devoted to the definition of a suitable cost function with appropriate constraints. In Sect. V, we summarize the numerical procedure and evaluate its performance by comparing against results obtained from employing a complementary optimization strategy. We then apply our numerical framework to one- and two vehicle systems. Finally, in Sect. VI, we conclude and point out directions for future research.

2. Geometric description

To describe the path of a pendulum in a vertical plane we introduce the arc length $s \in [0, s_{max}]$ as the curve parameter and denote the Cartesian coordinates of the trajectory in the plane as $\vec{U}(s) = (X(s), Y(s))$. The actual path can be calculated approximately using the standard model of a quasi–static moving point load on an ideal linear elastic cable, where the role of the hauling cable, as well as different possible boundary conditions and temperature effects are accounted for (Czitary, 1962; Rope dokumentation; CEN-Norm, 2009; Liedl, 1999). For a vehicle moving within a span away from a support, the trajectory can be approximated by a parabola. Closer to the support, as well as on the support, other curves are suitable. The support head itself consists of several circular arcs with different radii.

2.1. Simplified trajectories

In this work we use, as a first approximation, a simplified trajectory for the vehicle moving over a support, consisting of two straight lines and a circular arc. An extension of the model to more accurate paths is straightforward and lies beyond the focus of this investigation. Additionally, we assume a rigid behavior of the hauling cable, such that the velocities of both vehicles are equal in magnitude for all times. This approximation is well justified (a detailed investigation of the hauling cable dynamics requires quite some effort. For a study with moving weightless strings see (Banichuk et al., 2013; Andrianov and Awrejcewicz, 2006)).

The parametrization of the path for the vehicle is (see Fig. 1):

$$\vec{U}(s) = \begin{cases} \vec{f}_1(s), & \text{for } 0 \le s < s_i\,, \\ \vec{f}_2(s), & \text{for } s_i \le s < s_f\,, \\ \vec{f}_3(s), & \text{for } s_f \le s \le s_{max}\,, \end{cases} \tag{1}$$

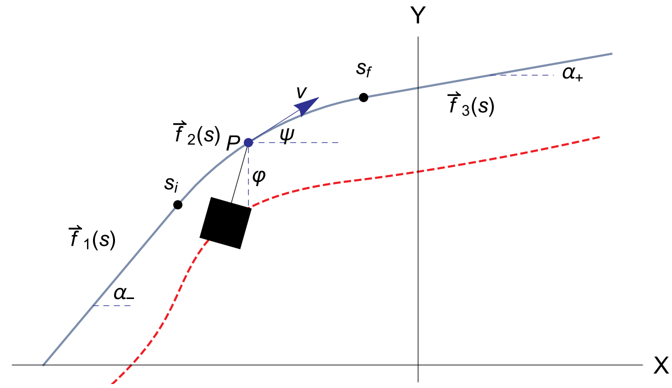

Fig. 1. Sketch of the model: the suspension point P of the physical pendulum moves with velocity v along the trajectory parametrized by the arc length s. The complete trajectory consists of three paths labeled by $\vec{f}_{1,2,3}(s)$, where $s_{i,f}$ denotes the initial/final points of the support structure. The velocity v is time (position) dependent and our design variable. The deflection angle φ is a dependent variable; ψ is the angle of the running gear respect to the horizontal (the axes are shown for orientation).

with

$$\vec{f}_1(s) = (s\cos\alpha_-\,,\, s\sin\alpha_-)\,, \tag{2}$$

$$\vec{f}_2(s) = \left(s_i\cos(\alpha_-) + r\sin(\alpha_-) - r\sin\left(\alpha_- - \frac{s-s_i}{r}\right),\, s_i\sin(\alpha_-) + r\cos\left(\alpha_- - \frac{s-s_i}{r}\right) - r\cos(\alpha_-)\right), \tag{3}$$

$$\vec{f}_3(s) = \left(s_i\cos(\alpha_-) + r\sin(\alpha_-) - r\sin(\alpha_+) + \left(s - s_f\right)\cos(\alpha_+)\,,\; s_i\sin(\alpha_-) + r\cos(\alpha_+) - r\cos(\alpha_-) + (s - s_f)\sin(\alpha_+)\right) \tag{4}$$

Here $s_f - s_i = r(\alpha_- - \alpha_+)$ is the length of the support head and r the radius of the arc respectively. We assume $\alpha_- \ge \alpha_+$, which means the support is not a hold–down clamp. In the two vehicle case, the parameters differ in general, $\alpha_\pm \to \alpha_\pm^{(1,2)}$, $r \to r^{(1,2)}$; s_{max} is equal for both vehicles (see Fig. 2). Using Eq. (1), several practical relevant problems can be formulated and solved by adjustment of the different parameters, e.g. two vehicles which pass the same support in the same time interval, or one vehicle which passes over a support and the other moves within a span, etc. Note that at the transition points $s = s_{i,f}$ the path curvature is discontinuous. This leads to discontinuities in the centrifugal acceleration of the vehicles, which can be cured if the support geometry is modeled through clothoids.

3. Equation of motion

Considering an ordinary pendulum, where the suspension point coordinates are time–dependent and located at $(X_P(t), Y_P(t)) \equiv (X(s(t)), Y(s(t)))$, the equation of motion for the angle (the derivation using a suitable Lagrangian is straightforward (Landau and Lifschitz, 2011)) $\varphi(t)$ is given by,

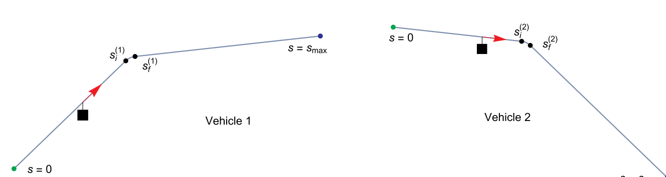

Fig. 2. Two vehicles moving along different paths; due to the coupling through the hauling cable, both vehicles have the same velocity at each instant of time. They cover the same distance s_{max}.