Analysis of a cable model, considering mass and wave oscillations

Ignacio García-Fernández, Marta Pla-Castells and Rafael J. Martínez-Durá

Instituto de Robótica, Universidad de Valencia. PO-Box 2085. 46071 - Valencia. Spain

Abstract. Theoretical cable-pulley dynamics models usually lead to computationally expensive numerical models. For this reason, both mass and cable oscillation are usually neglected when efficiency is an issue. Recently a new model has been presented that allows the simulation of cable oscillation and catenary with low computational cost. In this paper, we present a preliminary analysis of the dynamics of the model, based on numerical tests. More precisely, we analyze the influence of the main parameters of the model over its dynamics, taking as a reference the massless models used so far.

Keywords: Cable, pulley, real-time simulation, tower crane
PACS: 02.30.Jr,02.60.Lj,02.70.Bf,42.40.My

INTRODUCTION

Physically based modeling is one of the key subjects in computer graphics literature; training simulators, video-games, Virtual Reality applications for learning, etc. need a virtual environment in which every mechanical or logical system has to be properly modeled. Mechanical models need to be accurate enough to maximize the feeling of *presence* (the feeling of *being there*) and to achieve the particular goals of the application, but with a low computational cost. Within the range of Real-Time Computer Graphics (RTCG) applications, crane simulators have become a useful tool in many industry fields. In a crane simulator, complex mechanical systems of the machinery and of the loads are used. However, there is a lack in the modeling of pulley and cable dynamics, despite of the fact that they are the basis of load lift and of crane structure movement in most cases.

Cable dynamics has been extensively studied from different modeling methodologies [1, 2, 3] leading, in most cases, to non-linear partial differential equations [4, 5] or to finite element schemes [6, 7, 8]. These models, however, are addressed to achieve a good understanding of the problem or to an accurate simulation, useful for analysis or design. As a consequence, the associated numerical models are computationally intensive and not adequate for RTCG applications. For this reason, crane simulators often rely on cable models that consider only its tension, neglecting any oscillation or variation of the cable properties through its length [9, 10, 11]. In such models,a cable passing through a set of pulleys is considered as a massless ideal elastic cable. In order to determine the dynamics of the system, the total length of the cable (the sum of distances between adjacent pulleys) is measured, and compared to its theoretical length. Then a force is applied to the affected bodies [11], by means of the Hooke law. However, the cable is not a dynamical system itself, but an external force applied to other bodies.

More recently, García-Fernández et al. [12] have introduced a model that also considers cable oscillation between two adjacent pulleys. In this later model, the cable is allowed to deform laterally between two pulleys, using a damped wave equation. Then, the tension of the cable is applied to the linked bodies in a similar manner as in massless, spring models. But in this case, the length of the cable is computed using the arc length of every section, including deformation. The result is a model that considers cable mass, and that provides an enhanced visual realism to the simulation.

In order to achieve a better understanding of the dynamics of the model proposed in [12], the influence of the different parameters have to be checked. In short paper we present the preliminary results of these tests; more precisely we present the tests that show the influence of the cable mass and the wave equation damping in the cable dynamics, compared to the massless case. The paper is organized as follows. In the next section, the numerical tests are described, with an explanation of the decisions taken, and the more relevant results obtained are exposed and analyzed. In the last section concluding remarks are given, together with the main work that still has to be done to conclude the analysis of the model.

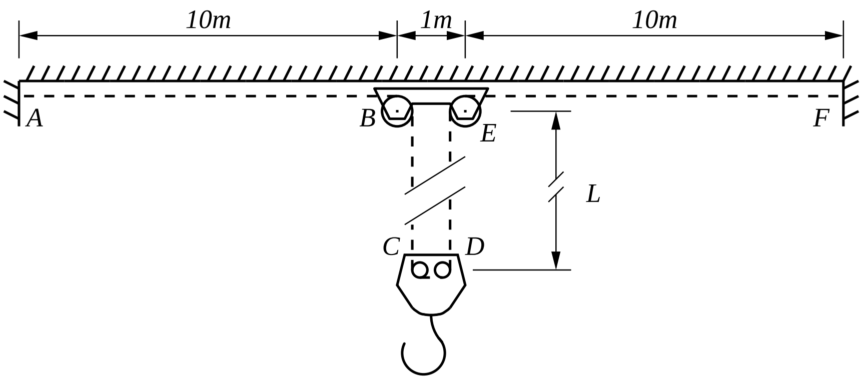

FIGURE 1. Scheme of the experimental setup, based on a tower crane hoist system. The cable is represented by a dashed line. L represents the cable length below the boom which, in this paper, is taken as $L = 10m$.

NUMERICAL TESTS

In crane models for training purposes, it is essential that the dynamics of the payload be similar to that of the real machine. If the main oscillation modes or the damping of the system are not properly reproduced, the trainee can acquire biased skills, which shall cause a lower quality in the training, and higher times of adaptation to the real machinery. For this reason, we shall analyze the pendulum period and the energy decay of the model presented in [12], in order to determine the influence of the introduction of the wave equation. In this work we shall study the effect of the two main parameters that determine the model [12]; cable density, and wave equation damping. In order to measure their influence, we shall compare the behavior of the model for different values of the parameters to that of the massless cable [11], which corresponds to the case when no oscillation is considered.

For the tests we shall consider the setup shown in Figure 1, based on a typical tower crane hoist configuration. Pulleys are placed at points B, C, D and E, providing a block and tackle mechanism, while points A and F constitute the points where the cable is linked by its extremes. Points A and F and pulleys B and E are attached to the crane boom, while pulleys C and D are linked to the hook. In our tests the distances shall be as follows; $AB = BC = DE = EF = 10m$, $CD = BE = 1m$. All the tests have been done using the same starting conditions; the payload placed vertically under the boom, with an initial horizontal velocity of 5m/s in the positive X axis. During the simulation, a linear damping 5% has been applied to payload velocity. The tests have been performed for the following cable densities: 0.4Kg/m, 0.8Kg/m, 1.2Kg/m, 1.6Kg/m to 2Kg/m. This set covers most of the used cables in tower cranes. Also, for every value of this set, five different values have been taken for the damping constant of the wave equation, between 0.2 and 1.0.

Evolution of Total Energy

In all the tests performed, decay of energy follows a similar scheme: first, there is a transient phase in which energy oscillates; then the energy decay is smoother (see Figure 2). As we shall show next, this transient oscillation can be related to the payload vertical movement caused by cable oscillation.

Influence of the Cable Density

First, we shall review the behavior of the cable when its density is modified, while the damping coefficient is kept constant (Figure 2-(a)). What is most relevant for our analysis is that, after the transient oscillations, the decay rate for the massless case (continuous curve in the figure), is tightly followed by the energy of the different models. Indeed, the different energy curves are lower bounded by the massless energy curve. This indicates that the model behaves properly in the middle to long term dynamics, at least within the tested range of parameters. Figure 2-(a) shows the results for a damping coefficient of 0.1. The figures obtained for the rest of damping values are similar, with shorter transient periods for higher oscillation damping, and are not shown.

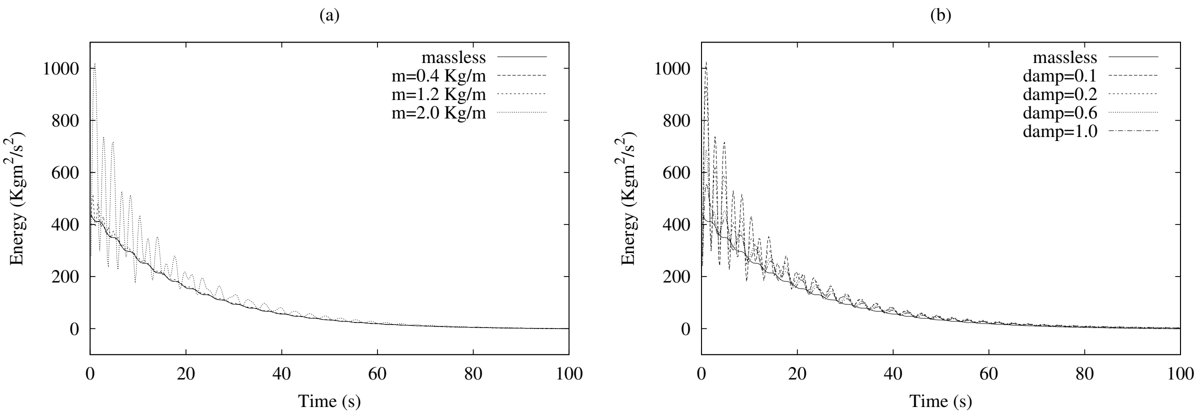

FIGURE 2. Evolution of the total mechanical energy of the payload. (a) Mechanical energy of the system along time for different density values, using a wave equation damping coefficient of 0.1. (b) Mechanical energy of the system along time for different wave equation damping coefficients, using a cable density of 2kg/m. See text for analysis.

Regarding the initial energy oscillation, it is the highest for larger density values. This fact can be explained if the oscillation corresponds to the injection of kinetic energy from the cable to the payload, which should be greater for more dense cables. The results obtained for cable damping, discussed next, tend to confirm this hypothesis.

Influence of the Wave Damping

Wave equation damping determines how quickly the oscillation of the cable fades out. Thus, for higher values of the damping parameter, it is expected that the dynamics tends to that of the massless cable more quickly. In fact, the performed tests show that, with high damping coefficients, the transient oscillation interval is narrower, leading to a behavior closer to that of the massless model (see Figure 2-(b)).

Pendulum Period

We have observed an influence of the oscillation model in the pendulum period. More precisely, we have observed a reduction of the frequency for higher values of the cable density. The x coordinate of the payload position for different cable densities has been plot in Figure 3-(a), showing this behavior. Again, the value of the wave equation damping in Figure 3-(b) is 0.1, but the results are essentially similar for the different tested values.

This period reduction can be explained by the catenary: for higher density, the larger catenary in the horizontal cable segments (sections AB and EF in Figure 1), causes a reduction of the pendulum length (variable L in Figure 1). This behavior is observed in real cranes. Indeed, according to the tests, there is no significant effect of the wave equation damping on pendulum period (see Figure 3-(b)). Thus, our hypothesis is that the only origin of the period reduction is the reduction of the cable length below the boom.

CONCLUSIONS

The results of the tests presented in this paper have shown that there is little influence of the parameters that have been analyzed over the payload dynamics. In addition, the observed effects are most probably due to dynamic properties of the pulley system, and not to the introduction of an oscillation model.

The influence of the oscillation model in the energy decay is limited to a transient initial phase, that is longer for lower values of the damping coefficient. But after this phase the evolution of the system has a similar asymptotic behavior than the massless model. In what regards pendulum period, there is a frequency increase for higher values

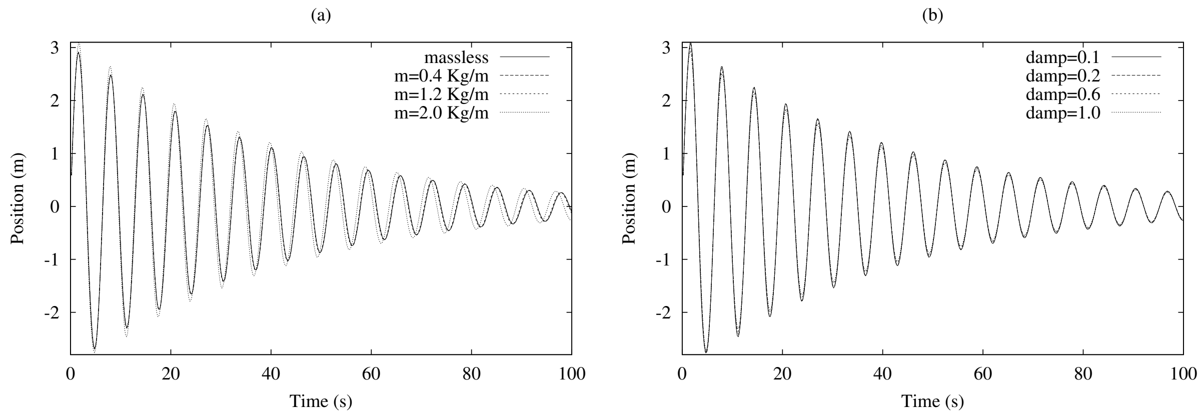

FIGURE 3. Evolution of the Position of the payload in the *x* axis along time. (a) Evolution of the position for different density values, using a wave equation damping coefficient of 0.1. (b) Evolution of the position for for different wave equation damping coefficients, using a cable density of 2kg/m. See text for analysis.

of the cable density, due to a reduction of the vertical cable segment. This behavior, however, was expected from our experience with real cranes, an cannot be reproduced with a massless cable.

Thus, the preliminary results that have been presented in this paper show that the use of our oscillation model is not likely to produce negative effects on the dynamics of the payload, while reproducing some effects not observable in the massless model, and providing with a better visual simulation in computer graphics applications.

In order to obtain more concluding results, we have the intention to perform further tests to confirm that the model can be safely used in the whole range of situations that are common during a tower crane operation. We shall review the test setup, in order to determine if the origin of the transient oscillations is cable movement, and whether this behavior is correct or not. Also, the tests have to be extended to have a complete description of the dynamics for most common situations: first, the same tests for different cable lengths and payload masses should be performed; second, the response of the payload to dynamic situations, such as trolley displacement (pulleys *B* and *E*) or cable length variation, shall be analyzed.

ACKNOWLEDGMENTS

This work has been partially supported by Ministerio de Industria y Energía of Spain, proj. FIT-340000-2006-290 and Ministerio de Fomento of Spain, proj. MFOM-NTRA-T61/2006.

REFERENCES

1. T. P. Dreyer, and J. H. V. Vuuren, *Applied Mathematical Modelling* **23**, 527–541 (1999).
2. M. Aufaure, *Computers and Structures* **74**, 243–251 (2000).
3. B. Radanovic, and F. R. Driscoll, "Development of an Efficien General Purpose Cable Model and Simulation for Marine Applications," in *Proceedings of the MTS/IEEE Oceans 2002 conference*, 2002, pp. 433–440.
4. Y. Zhang, and S. K. Agrawal, *Multibody Systems Dynamics* **15**, 287–304 (2006).
5. X. Arrasate, J. M. Abete, and S. Kaczmarczyk, "Distributed Longitudinal Vibration Model of a Lift System Including the Machine Dynamics," in *Proceedings of the 2nd IC-EpsMsO*, 2007.
6. M. Aufaure, *Computers and Structures* **46**, 807–812 (1993).
7. V. Gattulli, L. Martinelli, F. Perotti, and F. Vestroni, *Comp. Meth. in Appl. Mech. and Eng.* **193**, 69–85 (2004).
8. F. Ju, and Y. S. Choo, *International Journal of Solids and Structures* **42**, 3533–3547 (2005).
9. E. M. Abdel-Rahman, A. H. Nayef, and Z. N. Masoud, *Journal of vibration and Control* **9**, 863–908 (2003).
10. F. Ju, Y. Choo, and F. Cui, *International Journal of Solids and Structures* **43**, 376 – 389 (2006).
11. M. Servin, and C. Lacoursière, *Computer Graphics Forum* **26**, 172–184 (2007).
12. I. García-Fernández, M. Pla-Castells, and R. Martínez-Durá, "A Mixed Model for Real-Time, Interactive Simulation of a Cable Passing Through Several Pulleys," in *Proceedings of the International Conference of Numerical Analysis and Applied Mathematics*, 2007, pp. 212–215.