CSCanada
Management Science and Engineering
Vol. 12, No. 1, 2018, pp. 66-68
DOI:10.3968/10063

ISSN 1913-0341 [Print]
ISSN 1913-035X [Online]
www.cscanada.net
www.cscanada.org

The Effect of Bungee Cord's Parameters on the Safety of Bungee Jumpers

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Received 25 December 2017; accepted 19 January 2018
Published online 16 March 2018

Abstract
An abstract physical model is created to study the motion of a bungee jumper during a jump. With this model, the trajectory of the jumper is traced and the equations of motion are provided to describe the jumper's motion in detail. After the initial parameters of jumping are set, the jumper's trajectory is traced for different values of spring constant of the bungee cord, in order to investigate its effect on the jumper's safety. Later, Then a simulation experiment was performed with MATLAB in order to analyze the jumper's safety. The results can be used as a basis for assessing whether the spring constant of a bungee cord can guarantee the safety of jumpers under certain conditions. The study is expected to provide useful guidance on how to improve the safety of participants in this sport.

Key words: Bungee jumping; Bungee cord; Spring constant; Safety

Chen, C., Deng, K. Y, Fan, X. H., & Wang, H. (2018). The Effect of Bungee Cord's Parameters on the Safety of Bungee Jumpers .*Management Science and Engineering*, *12*(1), 66-68. Available from: URL: http://www.cscanada.net/index.php/mse/article/view/10063
DOI: http://dx.doi.org/10.3968/10063

INTRODUCTION

Bungee jumping is a dangerous and thrilling extreme sport. As a leisure activity, it has become popular among thrill seekers (Li, 2015) by virtue of its physical and mental challenges to the participants (Liu & Wu, 2006). However, the risky nature of this sport and increasing occurrence of injuries related to it exposes every participant to huge risk and stress. If the leisure activity does not guarantee safety, it will certainly lose popularity (Zhu, 2015). Therefore, it is very necessary to investigate the safety of participants in this sport.

Bungee jumping can be classified into different types based on the method of jumping (e.g. backward jumping with the bungee cord tied around the jumper's waist, forward jumping with the bungee cord tied around the jumper's waist, and bungee diving which involves dropping from a high platform above a water surface with the bungee cords tied around the jumper's ankles) and the location from which the jumper jumps (primarily bridge, tower, and bungee rocket).

There are slight differences in the pattern of jumper's motion between types of bungee jumping (Li, 2015). Existing physical models (Liu & Wu, 2006; Yue et al., 2000; Gomez et al., 1938) of bungee jump suggest that it is reasonable to regard such differences as negligible. Therefore, in order to simplify the problem and provide a relatively universal solution, this paper employs one model to generalize the motion of jumper dropped from a given location.

The state of a bungee jumper in motion is analyzed (Song, 2014; Ghorpade & Limaye, 2014; Xue, 2014; Peng, 2004; Liu, Huang, & Deng, 2005) and simulated (Du, 2016; Nie, Cheng, & Xi, 2017; Zhu, 2015; He, 2017; Yin, Li, & Li, 2017; Gomez et al., 2016) using the equations of motion combined with MATLAB and SIMULINK. The purpose of this study is to reveal the pattern and characteristics of the jumper's motion and identify the key factors affecting the safety, so as to provide guidance to help bungee-jumping equipment suppliers provide more reliable products.

1. ANALYSIS OF BUNGEE JUMP

1.1 Modeling

A model of bungee jump from a bridge is created in this paper.

Let k be the spring constant of the bungee cord used and x denote the position of the cord's lower end. The initial position of the cord's lower end, or the point on the bridge where the jump starts, is set at x=0, and x is positive at any point below the bridge. After the jumper falls, the cord will stretch and spring force provided by the stretched cord $t(x)$, can be expressed as

$$t(x)=-kx \qquad (1)$$

(Initial conditions: $x|_{t=0} = 0, \quad \dot{x}|_{t=0} = v_0 = 0$).

During an actual jump, the stretched cord should remain below the bridge. Then the equation of motion for the system has the following form:

$$m\ddot{x} = mg + t(x) - fz, \qquad (2)$$

where fz is air resistance.

With the help of MATLAB tools, we find that a quadratic polynomial provides a good fit to the measurements of air resistance and velocity (Ann & Bai, 2009).

The relationship between air resistance and the jumper's velocity can be described by

$$fz(x) = a_1\dot{x} + a_2|\dot{x}| \cdot \dot{x}. \qquad (3)$$

Substituting Equation (3) into Equation (2) gives the kinematic equation for this non-linear continuous system:

$$m\ddot{x} = mg + t(x) - a_1\dot{x} - a_2|\dot{x}| \cdot \dot{x}, \qquad (4)$$

where $a1$ and $a2$ are two fitting coefficients.

The values of $a1$ and $a2$ may vary, depending on the specific type of bungee jumping and actual conditions.

In this paper, $a1=a2=1$

1.2 Necessary Conditions for a Safe Bungee Jump

Safety is no small thing and special-purpose facilities, especially recreational ones, must guarantee the safety of all users. The spring constant of bungee cords used in bungee jumping are required to meet certain conditions in order to ensure that all jumps are safe (He, 2017). So this study tries to determine the k value range necessary for a safe jump.

The initial conditions set in this study are as follows:

Cord length: L=30 m; mass of the jumper: m=90 kg; height of the starting point above the ground: $x$max=80 m; gravitational acceleration: g=9.8 m/s^2.

Then the minimum k value that ensures safety, approximately 36, is computed with a program (This means that the when k=36, the jumper is slightly above the ground at the end of motion).

2. MATLAB SIMULATION

The motion of the jumper is simulated for various k values within the range of 20 to 50. The jumper's trajectories, $x(t)$-t, and the corresponding phase portraits, $v(t)$-t, are plotted (In the figures below, x=80 m indicates the starting point of jump, and x=0 m denotes a position at the ground).

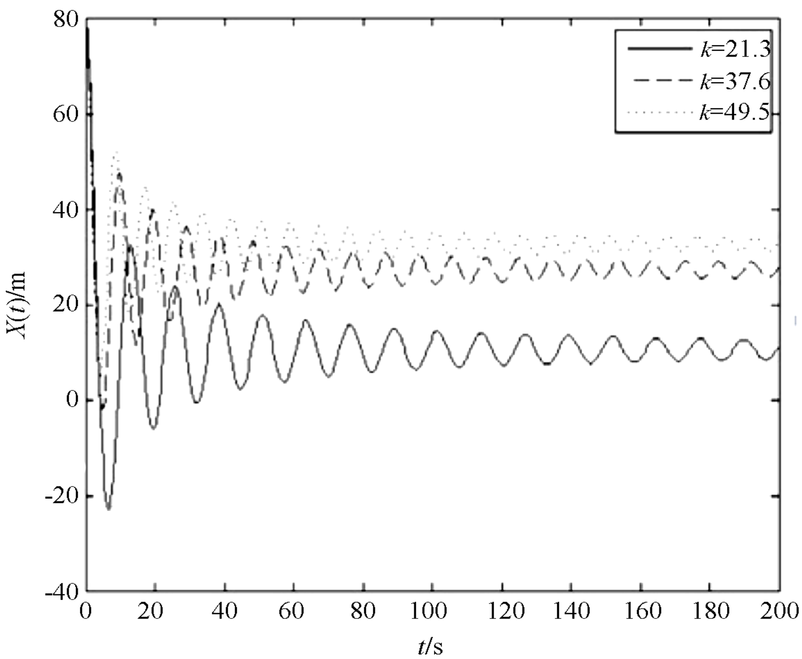

Figure 1
Trajectories for Different k Values ($x(t)$-t)

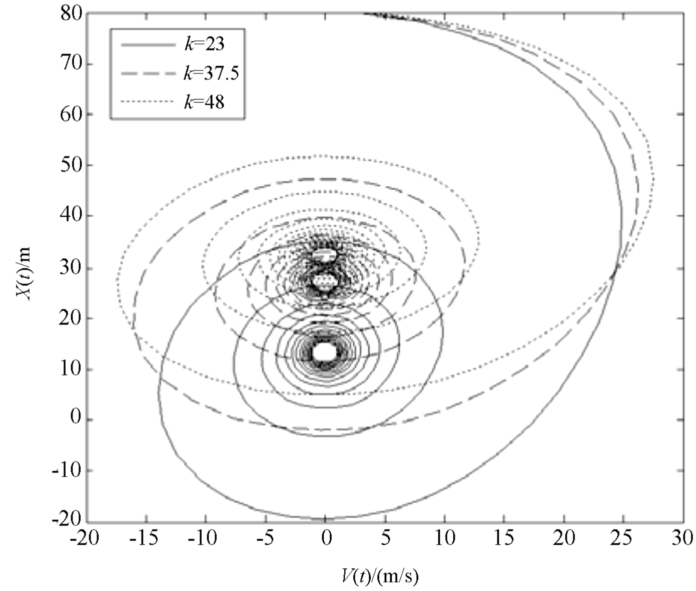

Figure 2
Phase Portraits for Different *k* Values (*v*(*t*)-*x*(*t*))

The figures above reveal that the spring constants that generate the black dashed lines and dotted lines can ensure the jumper's safety. When k=37.5 (black dashed lines), the lowest point the jumper reaches is at x=0 m and the corresponding velocity is nearly 0, which is consistent with the analytical result.

It follows that under given initial conditions, a cord with k>36 can guarantee the safety of jumpers.

CONCLUSION

The study concludes that the safety of bungee jumpers is closely related to the spring constant of the bungee cord used. The initial values of relevant parameters can be determined according to actual conditions and the trajectory of a jumper can then be traced accurately through the analytical and simulation methods described in this paper. The trajectory diagram obtained can help enhance safety in bungee jumping.

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