A MULTI-BODY DYNAMICS APPROACH TO A CABLE SIMULATION FOR KITES

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ABSTRACT

For the purpose of ultimately building a fully dynamic simulation of kites, an investigation is launched into a viable model of the cable with which the kite is attached to the ground. In the model proposed in this paper, only the slow modes of motion are taken into account due to the fact that only the slow motions have a real effect on the flight characteristics of the kite. Fast vibrations have a low amplitude with little effect. Also, by taking out all the fast modes of motion, the time step for integration can remain fairly large, speeding up the calculation process. Of special interest in the model is the damping which consists of aerodynamic damping and material-based damping. The relation between these two forms of damping is investigated. Verification of the model is done through comparison with analytical and real-life measured data. The resulting model is simulated in MSC ADAMS. It is shown that the aerodynamic damping is of prime interest because it dampens the slower motions. Material damping dampens mostly the fast vibrations.

KEY WORDS

Kites, cable, simulation, dynamic modelling, model development, Applications of simulation in engineering.

1. Introduction

Kite development has seen great improvements in the last 20 years. Today, kites are at the beginning of the next leap where they will be used for applications such as energy generation [6] and propelling ships [12]. Figure 1 shows an example of energy generation using kites. The system is called: the laddermill. The principle of the Laddermill [13] is simple. A series of kites is connected to a long tether. The other end of this tether is wound on a drum connected to a generator. While the kites ascend from, for example, 3000ft to 10000ft altitude, they pull the tether off the drum, driving the generator and creating electrical energy. The lift is maximized by attitude and maneuvering. Once the kites reach their maximum altitude, their angle of attack is changed so that they generate very little lift. The tether is retrieved by rotating the drum. Once the kites reach their low altitude floor again, their angle of attack is increased and the process

starts over. During retrieval of the cable, some energy will be spent. The difference in the energy created in the upward motion and the energy spent during the downward motion is the amount of energy created during one stroke. Figure 1 shows an artist impression of the laddermill system
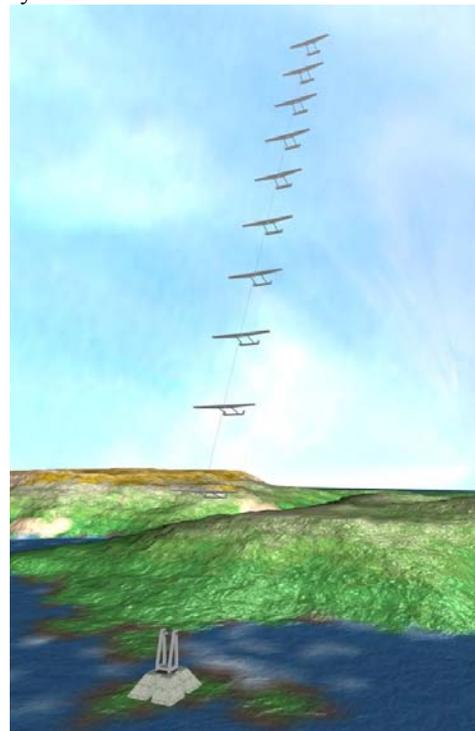

Figure 1, an artist impression of the laddermill.

Even though kites became more advanced, there was surprisingly little science involved in their design. The design process was largely based on empirical prototyping. But in this new leap, this is no longer a satisfactory approach. For applications like energy generation, the design of kites will have to be established using an optimization process. Kites are needed that fulfill the requirements with the utmost precision. In order to do any kind of optimization procedure, a thorough scientific understanding of a kite is required. In this paper, a multi-body dynamics approach is undertaken to model the cable of a kite.

2. Model requirements

Generally, the modes of motion in a cable can be divided into fast motions and slow motions. The fast motions are usually related to the high modulus of elasticity of the cable material. They are small in amplitude and travel through the cable very fast. The slow motions generally show a lot of inertia. They include waves that travel through the cable as a result of an excitation of some sort. In modelling the flight behaviour of kites, the very fast motions are of far lesser interest. Especially for cables made out of stiff materials such as Dyneema or Aramid, the fast motions are too fast and too short to have a significant impact on the stability of the kite. The slow motions, however, are able to tilt the cable force vector on the kite for a significant amount of time and therefore they have a large impact on the stability of the kite. Subsequently, taking the fast motions into account would mean that the time integration step would have to be extremely small. This would result in large calculation times. The model presented in this paper is meant to be a flexible design tool which is fast and intuitive to use.

3. The model

The cable model itself consists of a chain of discrete elements. These elements have a mass and they are infinitely stiff. Due to their infinite stiffness, they do not display any strain under loading. In reality, a cable will elongate under stress. But for high-tension fibers such as Dyneema and Aramid, this strain is so small it is of no real importance within the scope of this model. The cable elements are hinged together using two hook joints on each end, allowing it to hinge in every direction but preventing it from twisting.
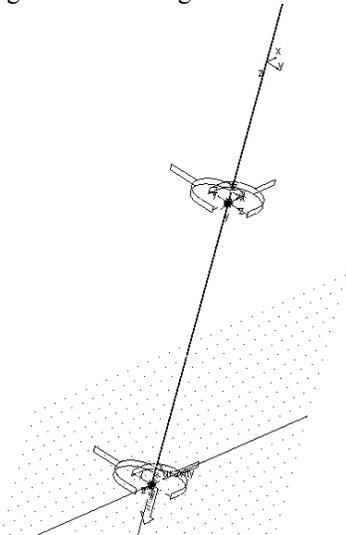

Figure 2, cable elements and hooke joints.

Twisting of the cable is a much faster motion than hinging or bending and it has little effect on the flight dynamics of the kite. It is taken out of the equation to keep the time

step from becoming too small. Figure 2 shows the cable elements and their hooke joints.

Damping of the cable motions comes in two forms. Aerodynamic damping and material-based damping. Aerodynamic damping, discussed on the next page, is damping due to aerodynamic drag of the cable element. The drag force on a cable element is always directed into the opposite direction of its velocity vector and will therefore have a damping effect. Material-based damping is the dissipation of kinetic energy through heat, created by fibers rubbing against each other as the cable is bent and flexed. This form of damping is dependent on the tension in the cable. In a kite line, the tension in the cable is not just a result of gravitational forces on the cable but also due to the lift of the kite. Evaluating the damping using a simple analytical pendulum model is not possible due to the pretension which greatly effects the material-based damping in the cable. For a cable we can say that the spring constant is equivalent to the tension divided by the element length. Therefore, the cable element equation of motion becomes:

$$\ddot{x} + \frac{c}{m}\dot{x} + \frac{T}{ml}x = 0 \tag{1}$$

This means that:

$$2\beta\omega_0 = \frac{c}{m} \tag{2}$$

And:

$$\omega_0^2 = \frac{T}{ml} \tag{3}$$

This results in the following equation:

$$c = 2\beta\sqrt{\frac{Tm}{l}} \tag{4}$$

For the rotational damping required here we divide by 1

$$c_{rot} = 2\beta\sqrt{\frac{Tm}{l^3}} \tag{5}$$

In equation 5 we see that the damping is dependent on the element length 1, the element mass m and tension T in the element. The factor β is in the order of 1% - 5%, which is representative value for cable dynamics. In the model, the damping is introduced in the joints using torsion springs which have no stiffness, only damping (see figure 3). Each rotational axis has its own damping spring. In this

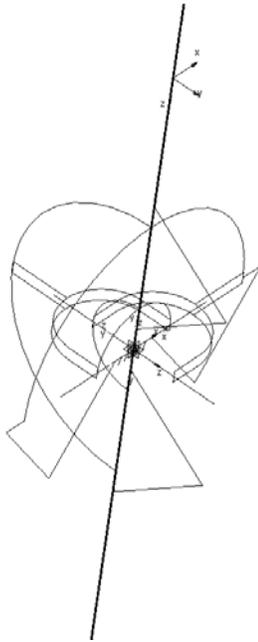case, two rotational axis, two hooke hinges and two damping springs.

Figure 3, the spring elements on the cable.

The second damping effect the cable experiences is due to aerodynamic forces. The aerodynamic drag is one of the most prominent forces on the cable and it consists of two velocity components. The first is the wind speed. The wind speed vector does not necessarily have to be horizontal and constant with altitude. With increasing altitude, the wind velocity will increase as well. A survey was done on 20 years worth of wind data provided by the royal Dutch meteorological institute (KNMI). Figure 4 shows the velocity profile.
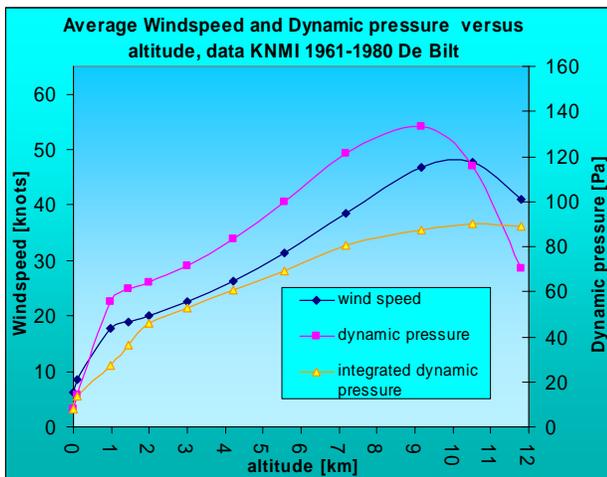

Figure 4, wind speed and dynamic pressure with altitude [5]

The second velocity component is that of the motion of the cable itself. While the cable moves, it experiences

drag in the opposite direction. For the aerodynamic drag, we can write:

$$D_x = C_D * \tfrac{1}{2} \rho(h)\left(V_{x_{wind}}(h) + V_{x_{cable}}\right)^2 *$$

$$2 * r * \sqrt{\left(y_b - y_a\right)^2 + \left(z_b - z_a\right)^2} \qquad (11)$$

$$D_y = C_D * \tfrac{1}{2} \rho(h)\left(V_{y_{wind}}(h) + V_{y_{cable}}\right)^2 *$$

$$2 * r * \sqrt{\left(x_b - x_a\right)^2 + \left(z_b - z_a\right)^2} \qquad (12)$$

$$D_z = C_D * \tfrac{1}{2} \rho(h)\left(V_{z_{wind}}(h) + V_{z_{cable}}\right)^2 *$$

$$2 * r * \sqrt{\left(y_b - y_a\right)^2 + \left(x_b - x_a\right)^2} \qquad (13)$$

In equations 11, 12 and 13, C_D is equal to 1.065 [11]. x, y and z are the coordinates of the endpoints of the element. The indices a and b indicate the lower and upper coordinate respectively. r is the cable radius and ρ is the air density. In the model, the aerodynamic drag on the kite is simulated as a three-axis force which acts on the center of the cable element. The x, y and z coordinates are in earth axis orientation. Figure 5 shows the final cable model.
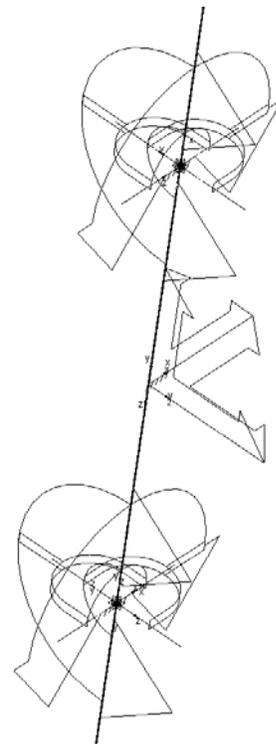

Figure 5, the cable element model

In order to approximate the situation of a kite, the bottom end of the cable is fixed to the ground and the top end of the cable has a constant lift force and drag force.

The model was built and simulated in MSC ADAMS (ADAMS view). Building such a model in ADAMS requires the user to place every element by hand, which is labour intensive. In order to quickly generate cables of different length, element length and element diameter, a program called "cable generator" was written in visual basic which generates the ADAMS model in the command file format. This generated command file can be imported into ADAMS directly. Initially, the cable is completely vertical. During simulation, the cable quickly seeks equilibrium between the lift force, drag force and aerodynamic force.

4. Verification

First verification must be made whether or not the cable generator program generates the models required. By comparing command files from the program with command files from hand-built models it was verified that the program indeed generates what is required. The second verification is in the field of the physics behind the model. In order to verify the physics, an analytically solvable situation and a real world measured situation are compared with their modelled counterpart. The first situation is a simple pendulum. For the period of a rod pendulum, we can write

$$P = 2\pi \sqrt{\frac{\frac{1}{3}ml^2}{\frac{1}{2}mgl}} = 2\pi \sqrt{\frac{2l}{3g}} \tag{14}$$

For a pendulum with a length of 1 meter, this results in a period of 1.638 seconds. Modelling this in ADAMS creates the following graph.
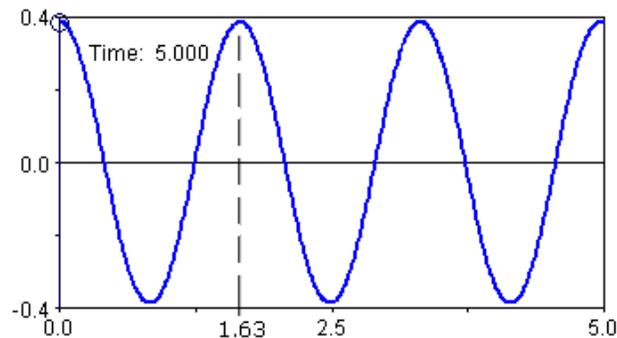

Figure 6, x coordinate of a swinging pendulum, modelled in ADAMS

As can be seen, the period of the motion closely resembles the analytical value.

The second case is a real world measured case where a 32-meter long tether was hung from the faculty building on a breezeless day. The tether had a radius of 4mm. The top of the tether was exitated and the time was measured

which it took for the maximum of the first wave to travel down to the other end of the tether. A large number of experiments were done which led to an average of 3.3 seconds.

The same situation was modelled in ADAMS using the proposed cable model. In this model, 32 elements were used with a length of 1 meter. At the top, the tether was exitated with the function:

$$F = 4\sin\left(8t + \frac{1}{2}\pi\right) \tag{15}$$

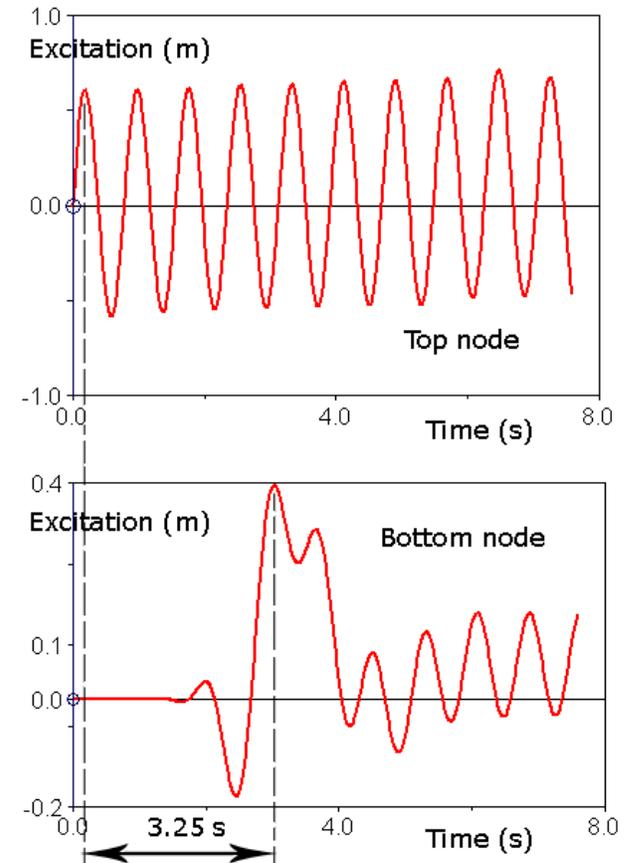Figure 7 shows the resulting graphs.

Figure 7, the exitation graphs of the free hanging tether.

As can be seen, the time for the first wave to travel down the tether is 3.25 seconds, which is very close to the measured 3.3 seconds.

A third verification is a verification of the numerical model. Because these simulations are done in ADAMS, the ADAMS code will alert the user when a numerical error becomes too great. No such warning was observed. Also, the accurate outcomes of the two previous cases give rise to the belief that the numerical analysis is performed properly.

5. Model convergence

The aim of the model proposed in this paper is to complement a larger simulation of kites. As such, it is important that the model is kept as lean as possible. The number of elements used in the model is of great influence on the speed with which the calculations can be made. In order to evaluate the sensitivity of the model to the number of elements used, several simulations were conducted with models of the same length (25 meters) but with ever increasing number of elements. Figure 8 shows the convergence at equilibrium. The two graphs represent the X and Y coordinates of the top of the cable after equilibrium is reached.
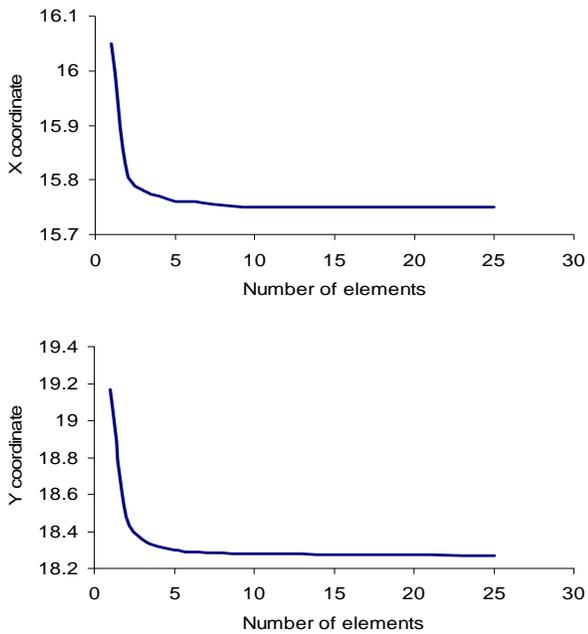

Figure 8, model convergence with number of elements.

As can be seen in figure 8, the model will quickly converges with increasing number of elements. For this model, no more than 6 elements would be enough to accurately describe the cable equilibrium.

6. Effective cable length

A long tether exhibits a large amount of inertia. For a kite on a long tether, this means that the motions of the kite do not necessarily travel all the way down the cable. The damping effect of the aerodynamic drag and the internal damping of the cable will ensure that only the top part of the cable will actually experience the motions of the kite. This holds true for small motions such as the motions a kite would exhibit when it experiences a wind gust. This effected length of the cable is called "effective cable length".

In order to grasp the effective cable length, the cable model proposed in this paper is used. A 50 element, 500 meter cable is generated using the cable generator program. A step function is used to excite the cable perpendicular to the lift and drag force. This excitation consists of a 20N force from t = 0.5s to t = 1s. The experiment is conducted at different values of material damping c.
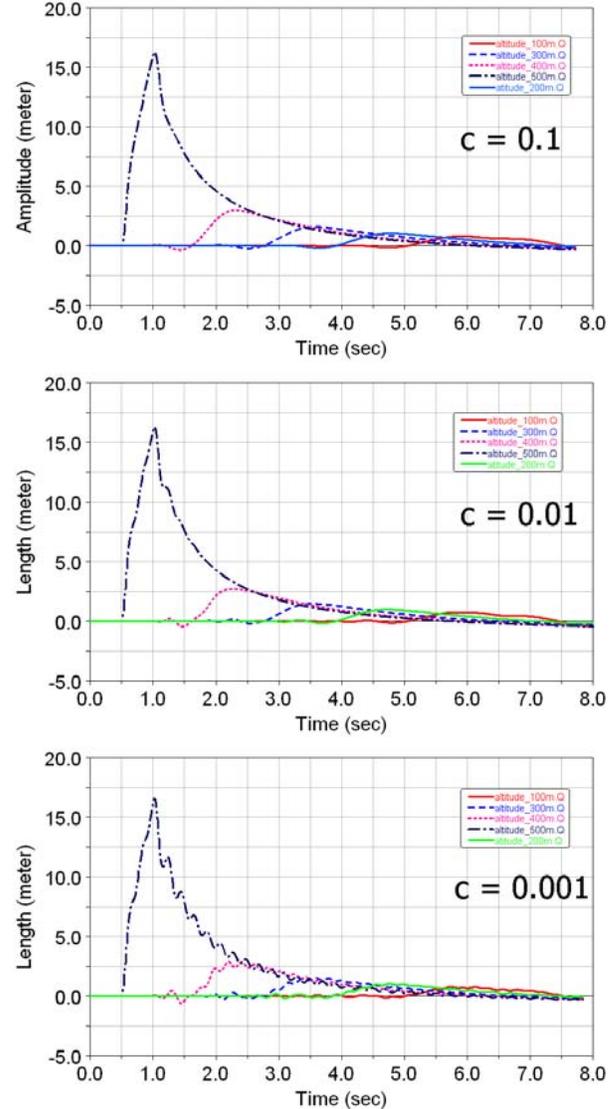

Figure 9, dissipation of an excitation along the cable with different values for material damping c.

As can be seen, the excitation quickly dissipates along the length of the cable. After 200 meters, the maximum amplitude in the cable is less than 10% of the amplitude in the top. What is interesting to note is that the different values of c seem to have no effect on the dissipation of the original excitation. The maximum amplitude at the top, as well as the maximum amplitudes along the cable are equal for all three values of c. The material damping seems to only smooth out the converging motion of the cable. At low values of c, the cable moves in a more erratic way. The material damping seems to merely dampen the faster, erratic motions and not the slower motions.

To study the effect of aerodynamic damping only, the same experiment is conducted, but now at a constant

value of c (c = 0.01). To vary the effect of the aerodynamic damping, the air density is varied. At ρ= 0, the experiment is effectively conducted in a vacuum and no aerodynamic drag exists.
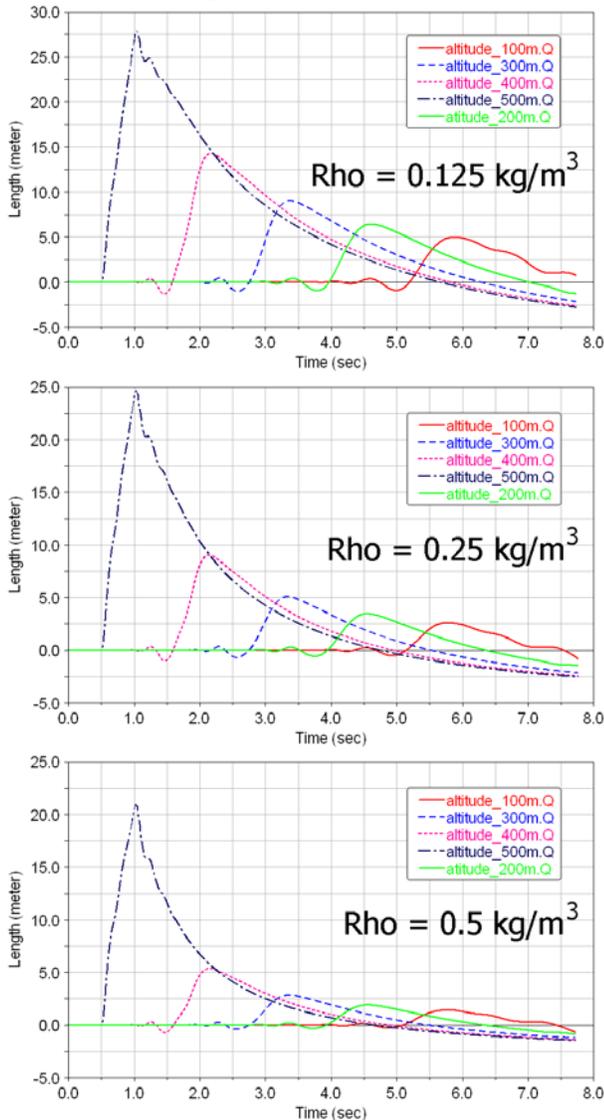

Figure 10, dissipation of an excitation along the cable with different values for air density (Rho).

Figure 10 shows that the peaks in the graphs still occur at the same points in time. The velocity at which the wave travels through the cable is constant. But the amount of dissipation varies quite significantly. At ρ= 0.125 kg/m^3, the maximum amplitude of the cable at 100m altitude is still about 20% of the maximum amplitude at the top of the cable. With increasing air density, the aerodynamic damping effect also quickly increases.

The two evaluations of aerodynamic and material damping show that material damping is most effective in fast vibration-like motions of the cable. The aerodynamic drag seems to dampen the slower motions. Since the slow motions are of prime interest in kite simulations, Aerodynamic damping seems the more interesting

parameter, although some material damping is required to keep the cable from showing extremely erratic motions.

7. Conclusions

The cable is an important aspect of kite dynamics. However, taking all the modes of motion into account will lead to a very slow simulation. The model proposed in this paper is a simplified model to only take into account the slow modes of motion. In such a model, it was shown that the aerodynamic drag is the most important mechanism of damping. Damping due to material properties is dependent on the tension in the cable. It mostly dampens out the faster vibrations which are not necessarily of great importance in kite simulations. There is, however, a need for some material damping to keep the cable from showing very erratic motions, but its exact value does not greatly influence the final effects the cable has on the flight characteristics of the kite

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