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Abstract

This paper discusses the maximum tension exerted on a massless rigid string that would allow Spider-Man to swing without it breaking. We model Spider-Man as a mass on a string and solve the equation of motion for a pendulum via Euler's Method to model the tension T throughout the string as a function of time. We found T_{max} to be 1964.55N, and then compared various materials to determine which would work best under each of their breakpoint limits. We found that a nylon-based string would not be able to support Spider-Man and we suggest he invest in spider dragline silk.

Introduction

We consider the idea of Spider-Man changing the material used in his web, then attempting to swing on it. If Spider-Man was simply hanging from his web then the tension, T in the string would be equal to his weight:

$$T = mg \tag{1}$$

where m is Spider-Man's mass (estimating as 75kg [1]), and $g = 9.81\text{ms}^{-2}$, the acceleration due to gravity. This would give a tension of 735.75N.

However, if Spider-Man was swinging on his web, like a pendulum, then the tension would be greater, as the string now needs to provide support for the centripetal force that keeps Spider-Man's path a circle. We model Spider-Man as a mass on a massless rigid string, swinging as a pendulum, to find the maximum tension in this swinging scenario. Then, finding substitute materials that Spider-Man could replace his web with.

Theory and Results

For a swinging massless rigid string, the tension T is given by [2]:

$$T(t) = m(g\cos\theta(t) + L\omega^2(t)) \tag{2}$$

where t is time, θ is the angle through the swing and ω is the angular velocity. To use this equation we are required to know how the angle θ changes as a function of time. The equation of motion for a pendulum is [3]:

$$\frac{d^2\theta}{dt^2} = -\frac{g}{L}\sin\theta \tag{3}$$

where L is the length of the pendulum (which we have arbitrarily chosen as 10m).

This was solved using Euler's Method [4] over a time period of 15s, with a time step $\Delta t = 0.001$s, this time step is small enough that it prevents the numerical instability that can be caused by Euler's method, also the model is simple enough that more sophisticated methods are not required. The simulation starts with an initial angle of 80° (measured with respect to the ground) and iterates through each time step, calculating the angle at each iteration. The update equations for this process are:

$$\theta_{n+1} = \theta_n + \Delta t\,\omega_n \tag{4}$$

$$\omega_{n+1} = \omega_n + \Delta t\left(-\frac{g}{L}\sin\theta_n\right) \tag{5}$$

After the angle is determined the tension is calculated using equation (2).

We can then plot all of the values for tension against time:

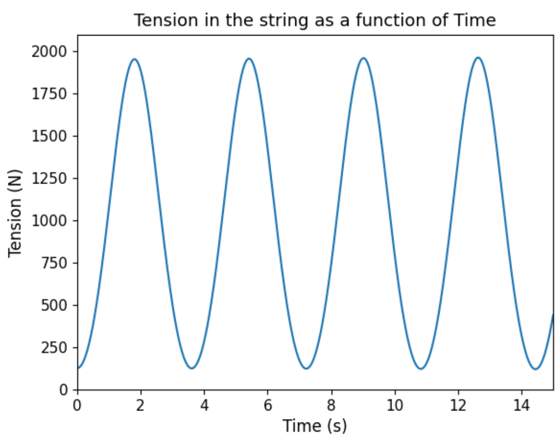

Figure 1: Plot of the tension in the string against time. The tension oscillates as expected for a pendulum with it peaking when Spider-Man is at the bottom of his swing ($\theta = 0$ and $\omega = 1.28\text{rad s}^{-1}$). The maximum value for tension is found to be 1964.55N. These values are taken directly from the simulation data

This maximum value for tension is approximately 2.5x more than in the static case.

Discussion

For comparison and feasibility, we have collated the tensile strengths of some web-like materials: Silkworm silk (Bombyx mori) [5], Spider dragline silk (Nephila) [5], Nylon [6] and, a peak human hair measure [7].

Assuming a cylindrical web shot of diameter 5mm, we calculate a cross-sectional area of $19.634 \times 10^{-6}\text{m}^2$. Then, by multiplying the breakpoint tensile strength (BTS) in pascals by this assumed cross-sectional area, we found the maximum tension force in newtons each of our materials could withstand if used as Spider-Man's webbing. These are shown as such:

Material	BTS	Max tension
Spider Dragline Silk	1300 MPa	25,524 N
Silkworm silk	500 MPa	9817 N
Human hair	270 MPa	5301 N
Nylon	62 MPa	1217 N

Table 1: Breakpoint tensile strength of materials and equivalent max tension at given cross-section area.

When comparing our maximum value for tension exerted on the web string, we can see that nylon would not be a feasible material as the max value experienced during the swing, 1964.55N, exceeds its breakpoint max tension. The other materials would comfortably support the swinging motion of Spider-Man, with natural silks demonstrating an immense max tension supported at relatively small cross-sectional area.

Conclusion

We modelled the tension in a massless rigid string by solving the equation of motion for a pendulum with Euler's method, and calculating the tension in the string for this swinging case. Clearly, the dragline silk is the optimal material; however, Spider-Man could even use human hair if he desired. We would recommend something with a higher tensile strength to support Spider-Man's other activities that require more heavy lifting using his webs.

References

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