A Guitar Capo: A Comparison of Compliant Mechanisms and Traditional Methods

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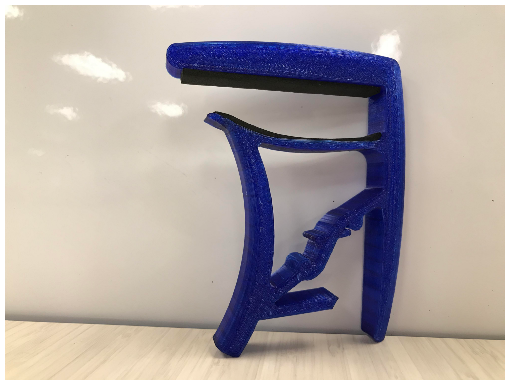


Figure 1: A prototype, compliant capo.

Contents

I Developing a Model

(a) A traditional capo. The action is based on a pin joint and a revolute spring, which forces down the strings of a guitar behind the chosen fret.

(b) A compliant capo. The revolute spring is replaced by members which provide resistance to deflection.

Figure 2

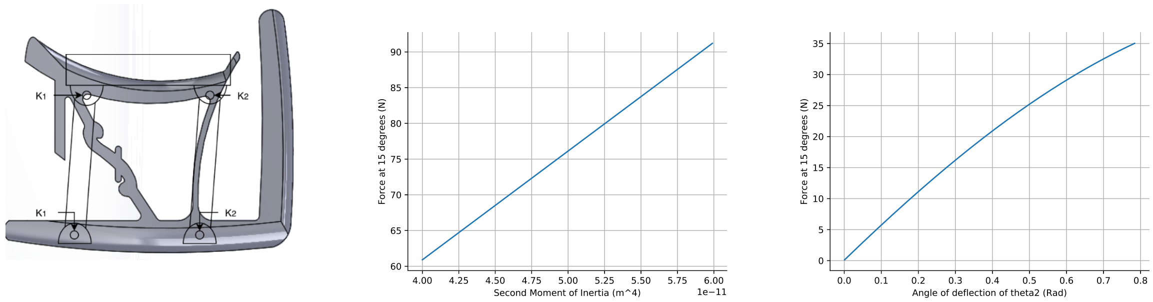
A capo, short for capadastro, which is Italian for "head of fretboard," is clamped onto the neck of a stringed instrument, such as a guitar, to change the effective length of the strings and therefore the pitch and key of the instrument [1]. The purpose of this project was to develop a capo which used principles of compliant mechanisms to improve on current methods.

Early designs of our mechanism relied on a simple cantilevered beam to store the energy that the capo uses to hold the strings against the fret. Unfortunately, this design wasn't able to effectively hold the strings with the necessary force without significant structural failure. Because of this, we moved away from the single-beam design by adding an additional structural element. You can see this in Fig. 2b, as the "forte f" connecting the two handles.

In later designs we developed an added connecting beam based on a four-bar mechanism design. This design is able to hold the necessary energy to accomplish all of the tasks of a capo in a simple, compact, and reliable way.

II Pseudo-Rigid Analysis

After coming up with a proposed design for a compliant capo, we developed a model to begin the process of optimization. Our initial design is is based on the four-bar linkage



(a) A kinematic diagram of the capos design.

(b)

(c)

Figure 3

shown in Fig. 3a, with two fixed-guided beams connecting the two handles, which are pressed together to operate the mechanism.

The model we developed rests on a few assumptions, the first of which is that we can neglect input forces. Instead, it is assumed that any user will be able to put the necessary forces on the capo to open the clamps. This is believed to be the case because the required force will necessarily be less than the force needed to press down the guitar strings, so long as the mechanical advantage is greater than one. Additionally, we assume that both connecting beams are the same width and thickness. Although this is not true in our own prototypes, this assumption is useful for approximating dimensions that can be refined in the later stages of design.

The goals of our model are to develop tools for sizing the compliant members in the capo, to choose a material to use in the realization of our results, and to analyze the effectiveness of the capo.

Prototype capos built in this report are all 3D printed, a manufacturing technique which greatly reduced cost during development, using PETG as their material. PETG has an elastic modulus of 3.15 GPa, and a yield strength of 62.8 MPa, which are used in several of our calculations [2].

Using these assumptions and equations in Appendix A, we derived a system for determining the force necessary to deflect the opening of the capo 15 degrees. You can see an example of this in Appendix B, written in the open-source programming language Python.

Figure 3c shows a graph of the results found using these equations while varying the second moment of inertia of both connecting beams. In this particular case, we used the material properties of PETG and the lengths from our prototype. These can both be seen in the example code provided in Appendix B.

III Material Selection

Given the dimensions found in Section II, we are interested in the characteristics of the model given a different material. Figure 4 shows a graph of the force needed to deflect the capo 15 degrees, much like in Figure 3c. In this graph, however, we have a constant moment of inertia of 5×10^{-11}meters^4 and, we vary the elastic modulus of the material.

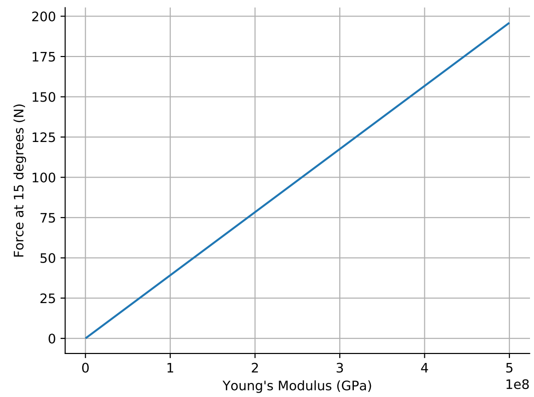
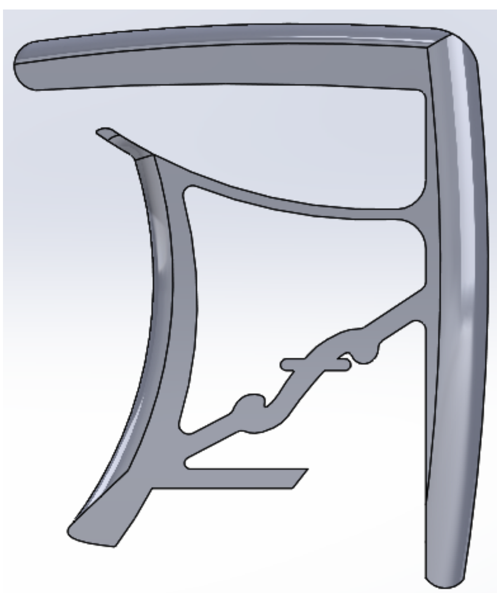


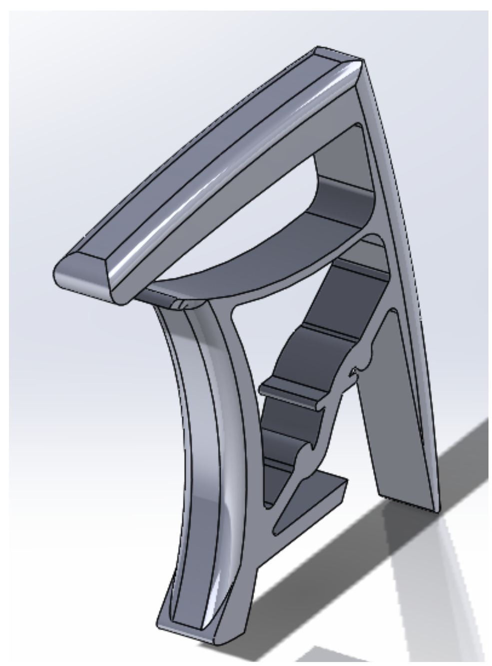
Figure 4

IV 3D Model

During the design phase, a model of the capo was made in SolidWorks, a drafting software, to allow the 3D printing of prototype capos. This model can be seen in Figure 5, and it is the same model used in all of the printed prototypes shown in this report.



(a) Front view of the design.



(b) Isometric view of the design.

Figure 5

V Alternate Projects

Before settling on the capo project we explored several other ideas, and, while they were never completed, they presented a great learning opportunity. For that reason, they are included in the report to reflect the experience of the team.

Self-Closing Door

The initial project idea for the team was a compliant hinge that would create bistable or self-closing behavior in a standard door. The idea was to use a four-bar mechanism, two of the links being the door and the wall. As the door opened, it would deflect a cantilevered beam bolted above the door and connected through a hinged link. This beam would store the energy necessary to force the door closed when it was released.

Upon further research, several problems were found with the design. Most significantly was the comparison of our project with the current market solutions. Current solutions utilize a similar four-bar system, but, instead of storing energy in a cantilevered beam, they use an attached spring. While the compliant reproduction of the system would be viable, it would require a large beam to allow the necessary deflection and does not necessarily hold any advantage in cost to the traditional model.

Another issue encountered was the manufacturing of a prototype. The forces and dimensions of the cantilevered beam suggest using materials difficult to manufacture without significant investment, such as steel, which has a much slower process for creating each subsequent prototype.

For these reasons, our design team decided it would be more productive to instead pursue other project ideas.

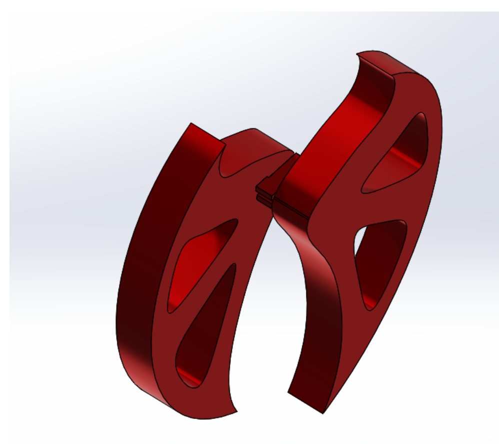


Figure 6: An early design for a compliant camming device. This is a photo of the 3D model printed to test the feasibility of the project.

Camming Device

The second proposed idea was a camming device (cam) for use in outdoor rock climbing. The hope was to design a cam with a compliant replacement for the spring and pin joint found in traditional models in order to reduce price of manufacturing, part count, and the risk of material interfering with the spring to eliminate a failure mode in the system.

While we designed and printed a prototype (Fig. 6), the materials on hand were insufficient for the fine details of the design. While this may be a feasible product, it was impractical to pursue as a project idea.

VI Benefits and Limitations of a Compliant Capo

The main benefit of this capo design is a reduced manufacturing cost due to producing only one part rather than many. Even assuming that the traditional models are assembled automatically, and that there is no cost of workers constructing the capos, manufacturing the new model will be faster and simpler. Additionally, the material costs will decrease considerably without the cost of the extruded steel wire.

There are drawbacks, however, with this design. One of the main issues issue stress relaxation. Unless measures are taken to prevent stress relaxation, there is a limited amount of time before the capo needs to be discarded. The second predicted issue is the lack of repairability. If a consumer is looking for a capo they can own and repair indefinitely they likely would prefer the traditional model where the individual parts are simpler and can be replaced.

That being said, there is such a benefit to reducing costs that it likely won't matter that the capos have a lifespan.

VII Possible Improvements

The prototypes completed at this time have limitations that we would like to see improved upon. The first issue we would like to correct is the manufacturing process. In our current model, we are 3D printing layers of plastic, which are delaminating and creating gaps in areas of high stress. If we were able to make the capos out of a more continuous material, such as an injection molded plastic or cast aluminum, this issue would likely improve.

Another issue has been stress relaxation. We have yet to run a fatigue analysis of the model, nor has any cycling experimentation been reliably performed (though we have noticed its effects in prototypes). With more time, we could find a balance of stresses and material, to prevent stress relaxation from impacting the performance of the capo.

An issue we haven't been concerned with yet, but would likely need to correct before commercialization, is the visual and tactile aesthetic of the capos. To start, we have already ingratiated musical icons into the shape of the model. However, we would also like to paint the capos with a thick rubberized material to distribute forces on the instruments and allow the capos to be made colorful.

Additionally, before commercialization, we would like to pursue the ability to customize the symbols in the lower connecting beam. If the customer could order online and put whatever symbol they wanted in the capo that would be another major benefit of our model. However, if that didn't work out it would still be possible to provide a multitude of options without any cost to the manufacturer.

A Appendix: Equations

All equations are from Larry L. Howell's *Compliant Mechanism's*

General

$$\tag{1}$$

$$k = 2\gamma\Theta_K \frac{EI}{l} \quad \text{Spring stiffness of fixed-guided beams} \tag{2}$$

$$\sigma_{max} = \frac{Fac}{2I} \quad \text{Max stress in a fixed-guided beam} \tag{3}$$

Virtual Work

$$\tag{4}$$

$$A = (-1 * X * a2) * s + T1 + T2 \tag{5}$$

$$B = -(T_2 + T_3) \tag{6}$$

$$C = T_3 + T_4 \tag{7}$$

$$h_{32} = \left(\frac{r_2 * \sin\theta_4 - \theta_2}{r_3 * \sin\theta_3 - \theta_4}\right) \tag{8}$$

$$h_{42} = \left(\frac{r_2 * \sin\theta_3 - \theta_2}{r_4 * \sin\theta_3 - \theta_4}\right) \tag{9}$$

$$dW = (A + h_{32}B + h_{42}C)\,\partial(\theta_2) \tag{10}$$

B Appendix: Code Example

A python script showing the process of finding the force needed to open the capo with varying moment of inertia.

```python
#Importing libraries
import matplotlib.pyplot as plt #plotting tools
```

```python
import numpy as np #matrix tools
from sympy import * #symbolic equation manipulator
from mpmath import * #symbolic math

#Creating symbolic variables and assigning values
a2, k1, k3 = symbols("a2 k1 k3") #See kinematic diagram
r2, r3, r4 = symbols("r2 r3 r4")
theta2, theta3, theta4 = symbols("theta2 theta3 theta4")
dtheta2, dtheta3, dtheta4 = symbols("dtheta2 dtheta3 dtheta4")#d as in delta
r1 = 0.0165
r2 = 0.044
r3 = 0.0508
r4 = 0.0508
theta2 = pi/2
theta3 = 0
theta4 = pi/2
b = 0.01
h = 0.004
E = 6.28*10**7

#instantiating arrays for loop outputs
var=[]
y=[]

for i in np.arange(4*10**-11, 6*10**-11, 10**-13):#creating a loop
    X = symbols("X")#renewing a fresh variable for each loop
    I = i#setting moment of inertia to fresh value

    #Solving for intermediate values
    d = (r1**2 + r2**2 - 2*r1*r2*cos(theta2))**0.5
    B = acos((r1**2 + d**2 - r2**2)/(2*r1*d))
    P = acos((r3**2 + d**2 - r4**2)/(2*r3*d))
    L = acos((r4**2 + d**2 - r3**2)/(2*r4*d))

    dtheta2 = pi/12
    dtheta3 = P + B
    dtheta4 = pi - (L + B)
    k1 = 2*2.2525*E*I/r1
    k3 = 2*2.2525*E*I/r3

    T1 = k1*dtheta2
    T2 = k1*(dtheta2 - dtheta3)
```

```
    T3 = k3*(dtheta4 - dtheta3)
    T4 = k3*dtheta4
    a2 = r2 / 2

    #Solving for equation inputs
    s = sin(theta2)
    A = (-1*X*a2) * s + T1 + T2
    B = -T2 - T3
    C = T3 + T4

    h32 = (r2 * sin(theta4 - theta2)) / (r3 * sin(theta3 - theta4))
    h42 = (r2 * sin(theta3 - theta2)) / (r4 * sin(theta3 - theta4))

    #Solving for outputs, dW is 0 by default
    dW = (A + B*h32 + C*h42)*dtheta2
    X = solve(dW,X)
    var.append(i) #putting outputs in a plottable array
    y.append(X[0])
plt.plot(var,y)
```

List of Figures

References

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