Design and Analysis of Catapult Launched Mechanism for UAV

[1]Imran Tariq , [2]Muhammad Noman Arshad
Department of Aeronautics & Astronautics
Institute of Space Technology
Islamabad, Pakistan
[1]imran.ist@live.com
[2]noman.arshad7@gmail.com

Abstract*—This paper covers the theoretical design and fabrication of catapult launched mechanism for Unmanned Aerial Vehicles (UAV). Many types of catapult launching devices have been developed so far but this paper emphasizes on the packable, easy to carry and portable launching device. After analyzing the pros and cons of different types of launching devices, Bungee Cord Mechanism is selected which is not as good as modern Launching Devices, however, it has much practical implications and advantages like: easy maintenance, lesser components and easy assembly. After structural (bending and weight) analysis of various materials like wood, iron, steel, brass and heat treated Aluminum Extruded Channel. From the analyzed materials heat treated Aluminum Extruded Channel is selected for main railing. Takeoff Velocity, acceleration, displacement and time are calculated after obtaining partial differential equations from the mathematical modeling of the system. Analysis of the effect of the aerodynamic lift and drag forces on the mathematical and mechanical/physical models is done also. Tradeoff study of displacement, velocity and acceleration with respect to stiffness of the cord is done to obtain a range of bungee cord elasticity for practical purpose. Adjustable wheel base cradle assembly is designed to carry different type of UAVs to meet the general customer requirements. Lock Mechanism for the cradle when bungee is stretched. Lock mechanism is designed on the basis of pistol trigger principle. Detailed 3D design was done before manufacturing. Results obtained after the manufacturing of final product are comparable with our theoretical design which proves the concept of launching UAVs in short time and effectively provide the takeoff velocity within 10 feet.

***Keywords*—UAV,LaunchingDevice(LD),Catapult, Mathematical Model.**

I. INTRODUCTION

UAV catapult is a device used to launch the Unmanned Aerial Vehicle. Numerous systems of launching devices have been made for UAVs so far. As the size, ranges value and performance of UAVs increases so new ways are being developed to ensure the safety and cost-effectiveness of launch and recovery systems. During their use, merits and demerits of each individual launching device were observed. By seeing our requirements and affordable conditions, this headed to the result that a launching mechanism should be light weight, minimum man power must be required to operate the launching device, it should have the possibility to be set up and to launch a UAV within fifteen minutes and it should cover the small volume. These are the main factors which need to be considered and incorporated into the conceptual design of launching device. The total cost of launching device and maintenance cost is also important for commercial point of view.

II. METHODOLOGY

A. Assumptions

I. Mass of elastic cord is neglected

II. System is considered as dynamic system because the UAV and the cradle travel linearly on the inclined plane.

III. Mass of rollers is neglected. Actually these neglected masses exist in dynamic system but effects are compensated by the energy reserve in the elastic cords.

IV. Elastic cord friction over the roller is neglected. The reason is that the rollers are small in size and are given its own rotation due to which friction force of elastic cord over the rollers considerably reduces and is neglected.

V. Tension in elastic cord (T) and horizontal reaction force (R_x) are coplanar to the inclined plane because tension and horizontal component of reaction force acts on the same inclined plane. Similarly, vertical component of reaction force and normal reaction acts in same direction that's why R_z and N are collinear.

VI. Frictional force work is neglected. The reason is that when the UAV slips off the cradle, friction force works which is comparatively small due to short run distance and that's why it is neglected. All these neglected friction forces are compensated by the energy reserve in the elastic cords.

VII. Stiffness of elastic cords is constant because it depends upon material.

VIII. UAV drag and lift force is neglected. This assumption is taken into account in order to simply the mathematical equations used below. Primarily, this lifting force (R_z) and drag force (Rx) reduces the sliding frictional force (F_μ) to some extent.

IX. Propeller pulling force or thrust (T) is constant because value of thrust decreases as speed increases so average constant value of thrust is assumed.

B. *Mathematical Modeling*

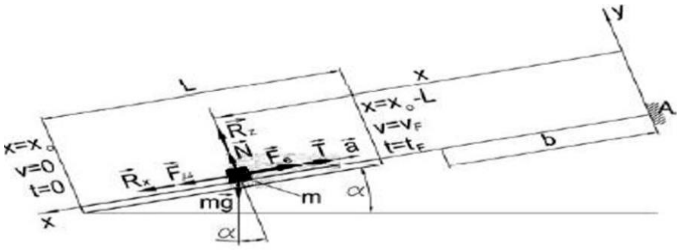

Figure 1 FBD of Launcher

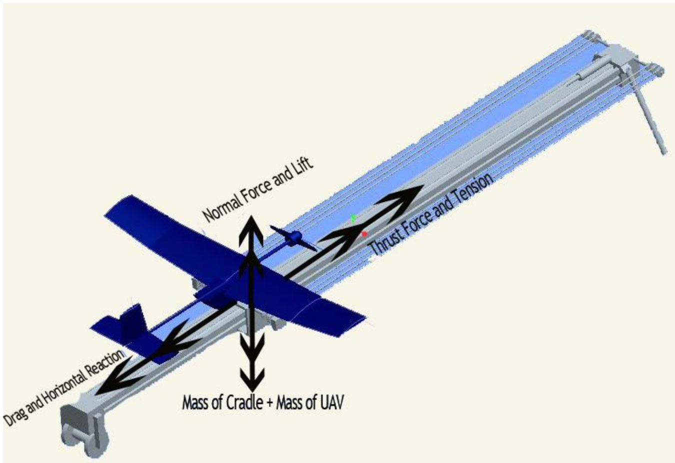

Figure 2 Schematic Diagram of LD

Eq. of motion of free particles in a vector form is:

$$ma = F_e + F_\mu + R_z + R_x + T + N \text{----------} \ (a)$$

$$Elastic\ Force = F_e = q(e - b)$$

$$Propeller\ Thrust\ Force = T = T_0\left(1 - \frac{\dot{x}}{V_s}\right) \cong T(\dot{x})$$

$$Drag\ Force = R_x = \frac{1}{2}\rho V^2 C_x S$$

$$Frictional\ Force = F_\mu = \mu N$$

$$Total\ mass = m = m_{UAV} + m_{CRD}$$

$$Lifting\ Force = R_z = \frac{1}{2}\rho V^2 C_z S$$

Now, by applying the assumptions i.e. neglecting R_x and putting $R_z = mg$

$$ma = F_e + T + F_\mu + mg + N$$

As, the particle motion is linear so by taking projections on "x" and "y" axis,
Hence,

In x-direction:

$$m\ddot{x} = F_\mu + mg\sin\alpha - F_e - T$$

In y-direction:

$$N = mg\cos\alpha$$

Then,

$$\ddot{x} + \frac{q}{m}x = g(\sin\alpha + \mu\cos\alpha) + \frac{q}{m}b - \frac{T}{m}$$

As we know that above equation is non-homogenous whose solution is:

$$Displacement = x(t)$$
$$= C_1\cos\sqrt{\frac{q}{m}}t + C_2\sin\sqrt{\frac{q}{m}}t + \frac{mg}{q}(\sin\alpha + \mu\cos\alpha) + b - \frac{T}{q}$$

As,

Initial Conditions are: $t = 0$, $x = x_0$, $\dot{x_0} = 0$

$$C_1 = x_0 + \frac{T}{q} - \frac{mg}{q}(\sin\alpha + \mu\cos\alpha) - b$$

$$C_2 = 0$$

By putting the values of constants and by simplifying, we get the equation:

$$x(t) = \left[\frac{T}{q} + x_0 - \frac{mg}{q}(\sin\alpha + \mu\cos\alpha) - b\right]\cos\sqrt{\frac{q}{m}}t + \frac{mg}{q}(\sin\alpha + \mu\cos\alpha) + b - \frac{T}{q}$$

By differentiating, we get the velocity eq.

$$Velocity = \dot{x}(t) = -\left[\frac{T}{q} + x_0 - \frac{mg}{q}(\sin\alpha + \mu\cos\alpha) - b\right]\sqrt{\frac{q}{m}}\sin\sqrt{\frac{q}{m}}t$$

As final conditions are:

$$t = t_F$$
$$x(t_F) = x_0 - L$$

So,

$$t_F = \sqrt{\frac{m}{q}}\cos^{-1}\left[\frac{x(t_F) - \frac{mg}{q}(\sin\alpha + \mu\cos\alpha) - b + \frac{T}{q}}{x_0 + \frac{T}{q} - \frac{mg}{q}(\sin\alpha + \mu\cos\alpha) - b}\right]$$

By differentiating the velocity equation, we get the acceleration eq.

$$Acceleration = \ddot{x}(t)$$
$$= -\left[\frac{T}{q} + x_0 - \frac{mg}{q}(\sin\alpha + \mu\cos\alpha) - b\right]\frac{q}{m}\cos\sqrt{\frac{q}{m}}$$

III. Theoretical Design

A. *Known Parameters*

Few of the parameters were known to us by our design requirement and the software tools like Pro-E designing used to determine the weight of the subassemblies of the model.

Table 1 (Known Parameters)

Variables	Values	Remarks
Thrust (T)	1-8lbf	Available UAVS in the UAV Lab
Bungee Stiffness	0.675lbf/ft	Manufacturer's Data
Aluminum –Steel Static Frictional Coefficient	0.35	From Literature

Aluminum –Steel Dynamic Frictional Coefficient	0.25	From Literature
Initial Distance	Zero	Initial Condition
Mass of cradle	4.4lbs	Pro-E Weight Estimation
Mass of UAV	4.4-11lbs	Assumption

B. *Analysis*

i. *Velocity Vs Time Graph:*

By putting the values of all variables in velocity equation we get this graph.

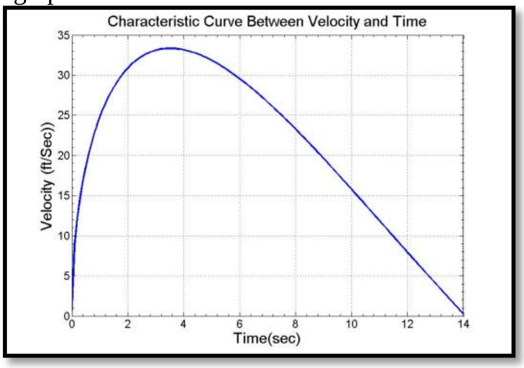

Figure 3 (Characteristic Curve between Velocity and Time)

Above graph shows that the moment the cradle is released the cradle moves with the velocity and after 0.5 seconds it reaches to 17ft/s (which is the takeoff velocity for the small UAV's[]) which means that it will cover 8.5ft. So, by adding safety factor of 0.15 we get the length of the railing to be the 10ft. It comes to rest after 1.4 seconds. The maximum velocity which can be obtained using stiffness 6.75lbf/ft and thrust an average of 4lbf is 34ft/sec theoretically. This Velocity is enough for a small UAV weighing 25lbs to takeoff within the railing distance.

ii. *Acceleration Vs Time Graph:*

By putting the values of all variables in velocity equation we get this graph.

The acceleration at first which the cradle has to face is around 9.9ft/sec^2. It then decelerates and after 2.5sec approximately approaching towards zero. This exposure to such a great value of acceleration will cause the structural failure. So, we will have to think about the structures integrity as well. The variation in the thrust from .4-8lbf with the thrust of 18N the max velocity achieved along with the stiffness of 6.75lbf/ft is 35ft/s and it can be improved by the combination of both the parameters

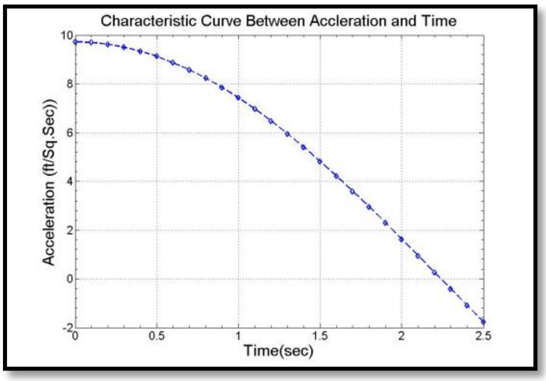

Figure 4 (Characteristic Curve between Acceleration and Time)

C. *Trade off Study*

i. *Velocity Vs Time Graph (By varying Thrust):*

By varying thrust values we get following graph between velocity and time from velocity equation

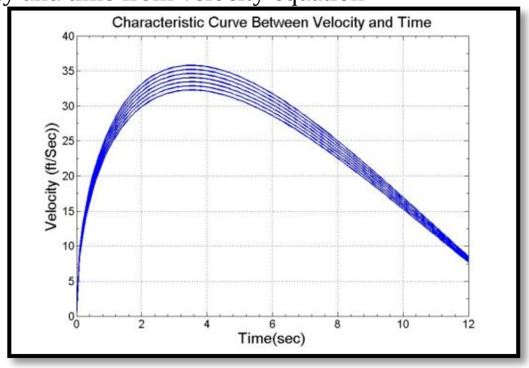

Figure 3 (Graph of Velocity Vs Time with Variation in Thrust

However, the thrust affect is very little we should mainly focus on the bungee cord stiffness variation

ii. *Velocity Vs Time Graph (By varying Stiffness):*

By varying stiffness value from 2-12lbf/ft, we get the following graph between velocity and time.

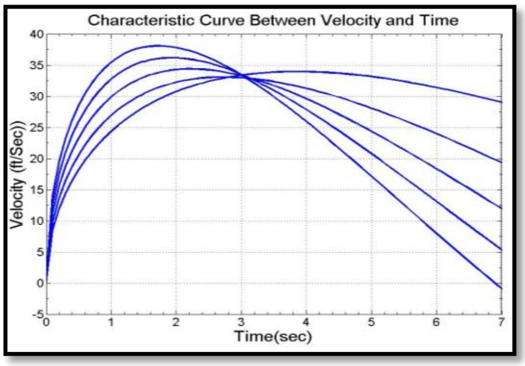

Figure 4 (Graph of Velocity Vs Time with Variation in Thrust

Above graph shows that the minimum stiffness 2lbf/ft meets our desired velocity 15ft/s. The increase in the stiffness will enhance our design. So, the prototype must have an option to add up the cords in parallel to increase the stiffness and increase the weight range.

IV. SIMULATIONS

A. *Pro E Mechanica Analysis*

i. 3DModeling

Using Pro-E application Mechanism the catapult was designed by parts in the Pro-Engineer WF5.0. Then parts were assembled in the assembly module. The Assembly of catapult is shown below (Figure 11)

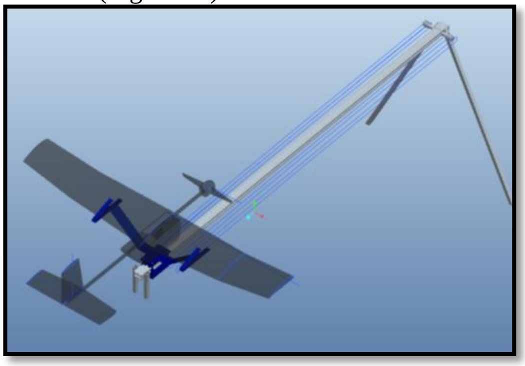

Figure 5 (Pro-E 3D Model of Catapult)

ii. Initial Setup (Mechanism Definition)

In Pro-E Mechanism the assembly was taken and the initial condition, joints, 3D roller frictional contacts and the elastic chord replaced with the springs with the equivalent elastic constants (2lbf/ft). Initial condition was input as the initial time and velocity are zero. The max translational limit was set to 9.8feet (as our railing is 10feet). The gravity and ground affects were enabled. Illustration of the above mentioned Mechanism is shown in Figure 12.

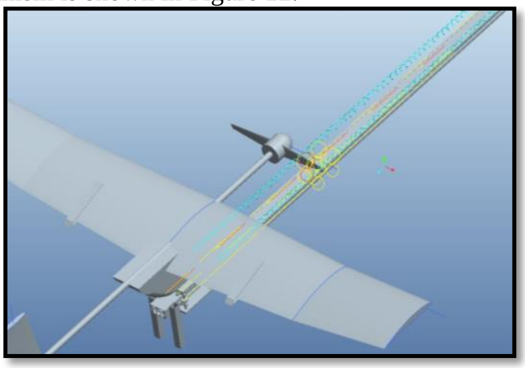

Figure 12 (Pro-E Mechanism Definition)

iii. Dynamic Analysis

Dynamic Analysis setting was done and analysis was run with the force direction in the positive Z-Axis. The cradle accelerated and achieved the desired velocity. Graphs between Velocity/Acceleration Vs time were plotted.

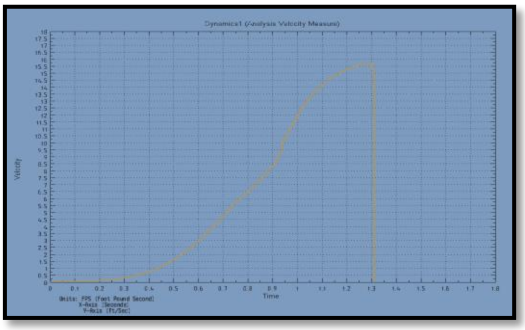

Figure 13 (Velocity Vs Time)

Velocity of the cradle shoots to 15.75ft/s in 1.3 seconds and when the cradle is reached to its constrain (as mentioned earlier) 9.8ft it stops and comes to rest.

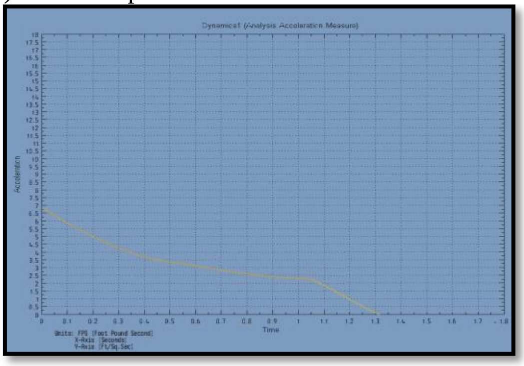

Figure 14 (Acceleration Vs Time)

Table 2 (Output Parameters listed from Fig 13 & 14)

Time(s)	Velocity ft/s	Acceleration ft/s^2
0	0	6.8
0.4	0.75	3.6
0.8	6.5	2.5
1.2	15.25	1
1.3	15.75	0

V. PROTOTYPE

i. Manufacturing

Prototype of the catapult was fabricated using the Institute of Space Technology Workshop facility and bungee cord with desired stiffness was attached to the prototype as shown in (Figure 15)

Figure 6 (Fabrication of Catapult Mechanism)

ii. Testing

Several tests were done using the desired bungee stiffness for a 2 kg aircraft and 2kg cradle weight (using electronic balance) with no thrust and distance covered (9.8ft) by the cradle with respect to time was observed. Data obtained from the best three test glides is listed below Table 3

Table 3 (Testing Results)

Observation	Time(s)	Velocity ft/s
1	0.8785	11.16
2	0.8244	11.89
3	1.0049	9.75
4	0.9874	9.92

VI. Conclusion

Theoretical design, simulations and the Testing comparison leads us to the summary of the catapult design which we can offer for our customers. The summary of the Launching device is given as below

Table 4 (Catapult Specification)

Length of Railing	10ft
Velocity	5-15ft/s
Acceleration	6-12ft/s^2
UAV Weight Range	Less than 17.6lbs
Total Weight	22lbs
Cord Stiffness	2-12lbf/ft

The UAV mass will define your launching speed and the stiffness cord selection. The theoretical design may not be reliable due to idealization. However, the practical and simulation results show that for every kg we have to add 2lbf/ft of stiffness. Moreover, an alternate option is to enhance the cord tension by making the length of the bungee cord short enough to its manufacturer's datasheet up to allowable extension.

VII. Acknowledgement

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