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Design, Fabrication and Testing of an Unmanned Aerial Vehicle Catapult Launcher

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Abstract: *The need for launching Unmanned Aerial Vehicles (UAVs) without the availability of a proper runway and in rough terrains, calls for the development of alternative launch mechanisms such as a catapult launcher. This paper involves the design process of a UAV launcher from a conceptual to a detailed phase with a focus on a bungee type catapult launcher. The design process includes identifying the critical design requirements, followed by developing a mathematical model in MATLAB which takes in the take-off speed requirement and helps in analyzing the motion of the cradle on the launcher by giving the energy requirements for the bungee cord. On the basis of these values appropriate selection of bungee cord is carried out. A final design has been proposed which was modeled on ABAQUS for structural analysis and material selection. Once the calculations have been verified, a prototype has been fabricated in-house with Aluminum CNC parts. It is finally tested by launching a flying wing UAV to validate the results of the mathematical model and structural analysis.*

Keywords: *Bungee, Catapult Launcher, UAV*

1. Introduction

In the present scenario where the need of UAVs for various applications [1] is increasing rapidly, there is a major focus on alternative launching methods to eliminate the need of a paved runway or open space. A Catapult Launcher allows the UAV to be launched from almost everywhere like rough terrains, urban areas etc., and in a relatively short distances as well. This is essential since it isn't always possible to find open flat surfaces that can act as runways.

2. Conceptual Design

The Catapult Launcher is intended for a UAV of 2.1 meters wingspan with a maximum takeoff weight of 10 Kgs and takeoff speed requirement of 20 ms- 1. The aim is to validate the design of the launcher by flight testing a UAV with a self-fabricated launcher.

2.1 Critical Design Requirements

TABLE I: Requirement Analysis

Parameter	Value
Maximum UAV Weight	10 Kgs
Maximum Launch Speed	20 m/s
Maximum Acceleration	<4g
Launch Angle	Variable Based on UAV
Launcher Weight	<35 Kgs

In addition to these requirements, the launcher needs to be of a compact size with minimum set-up time to allow portability and quick deployment. Most importantly, it should ensure the safety of the operator and must be easy to operate with low maintenance. It is also required that it has adjustable launch angle to provide for different type of UAVs and wind conditions.

2.2 Design Concept Selection

In order to incorporate all the critical design requirements, various concepts were analyzed:

- Electric Winch Powered catapult launcher
- Pneumatic Catapult launcher
- Bungee powered catapult launcher
- Electromagnetic rail launcher

The analysis showed that a bungee launcher is suitable for UAV's up to 50 Kgs and it is a relatively cheap system compared to other systems. Even though Pneumatic launchers [2, 4] make up the majority of the launchers and are able to launch heavier UAVs, their cost is significantly higher and mostly comes in a huge size, thus creating problems in transportation. Since the bungee launcher fulfilled all the essential requirements, it was selected as the launch mechanism for the analysis.

2.3 General Functionality Structure

The design selected is a bungee catapult mechanism. The design works by pulling a certain number of the bungee cords back and simultaneously releasing them. The potential energy stored in the bungee accelerates the cradle carrying the UAV along the rail and imparts the necessary takeoff speed.

Fig. 1: Launcher functionality's four main functions

3. Preliminary Design

3.1 Engineering Calculations

It is required to calculate the energy requirements of the bungees along with the ramp length of the launcher. The main variables to consider are:

- Mass of UAV and launcher's cradle
- The aerodynamic drag
- Angle of elevation
- Stiffness of bungee
- Friction resistance on wheel bearings

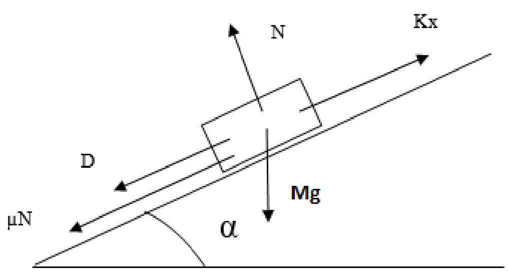

Fig. 2: Force Analysis of the UAV

The figure depicts the various forces acting on the UAV and the cradle system at the time of the release where the whole system is assumed to be in equilibrium resulting in the following equation:

$$Ma = F = Kx - D - \mu N - Mg\sin\alpha \quad (1)$$

$$Ma = F = Kx - D - \mu Mg\cos\alpha - Mg\sin\alpha \quad (2)$$

$$D = 1/2\ [\rho\ V^2\ C_d\ A] \quad (3)$$

Where the symbols have their usual meanings, M represents combined masses of UAV and Cradle, a represents maximum acceleration (corresponding 20 m/s velocity), *K* represents the spring force of the bungee, *D* represents the aerodynamic drag, *x* is the bungee extension and μ is the co-efficient of friction.

The drag force [3] varies with velocity but is assumed to constant throughout, at its maximum value to simplify the equation. The maximum drag force is calculated using the equation (3) and is taken to be approximately 45 N.

The equations [5] have been derived with the assumption that the contribution of the weight of the bungee cords, UAV's propulsion thrust and the friction between the cradle and the UAV wings is negligible.

The following graph shows the Bungee Force required to launch the UAV with respect to the ramp angle and ramp length(i.e. Bungee extension: x). A code has been written on MATLAB to plot relationship between Force Vs. Ramp Length and Force Vs. Ramp Angle.

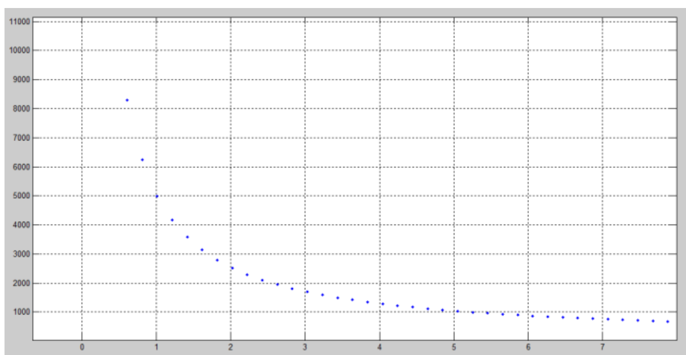

Fig. 3: Force (y-axis) Vs. Ramp Length (x-axis) at α = 12 Degrees

Ramp length of 3.2 meters has been chosen to keep the g-force acting on the UAV under the limit (3.5 g) as defined in the conceptual design requirements. Hence from the above graph it is seen that for a ramp length of 3.2 meters, a force of 1200 N is required to launch a UAV weighing 10 kgs at 20 m/s release velocity.

4.2 Bungee Stiffness Calculations

After calculating the bungee force requirements, length and the number of bungee cords need to be determined. Almost all the bungees available in the market do not sell them by a specific K value as it can be inferred from the given equation that it depends on the length of the bungee as well.

$$K = (\ E\ A_0\ )\ /\ (\ L_0\ ) \quad (4)$$

Where E is Young's modulus, a material constant, A_0 is the cross-sectional area of the material and L_0 is the unstretched length of the cord.

In order to derive the value of K, various types of bungees available in market has been tested by conducting an experiment and utilizing an instrument called force gauge to measure the value of the force at a given elongation. The results are shown below for the selected bungee with external diameter of 10 mm and internal diameter of 5 mm.

Fig. 4: Bungee Cord's Stiffness Constant Measurement

TABLE II: BUNGEE STIFFNESS CONSTANT

Force (N)	Unstretched Length(m)	Elongated Length (m)	Stiffness Constant K (N/m)
200	0.5	3.2	75
400	1	6.5	72
100	0.2	1.56	74
500	1.2	7.8	75

The stiffness of the bungee sample has been taken as 75 N/m. Therefore to achieve a force of 1200N, Elongated length of 3.2 m is needed. This has been obtained by using 6 bungees in parallel of unstretched length 0.53 m.

3.3 Design Concept Generation

With the engineering calculations in hand, various design alternatives [7] were studies and the parts were designed:

3.3.1 Cradle

Cradle length of 35cm has been chosen. This value allows comfortable mounting of different propeller to the specified UAV, with considerable margin. The geometry of the cradle has been designed in such a way that its inner surface coincides with the rails cross-section, and the thicknesses is enough to bear the load of the acceleration.

3.3.2 Rail section

The rail should have such a cross-section that maximizes the ratio of its stiffness (second moment of area) to its area, and is able to carry its own weight and the weights of the UAV. For such a purpose, an I-section would be ideal, however, to maximize compatibility with the carriages sliding mechanism, a rectangular section is preferred. The cradle sliding on the rail as seen in the below figure consists of 8 bearings.

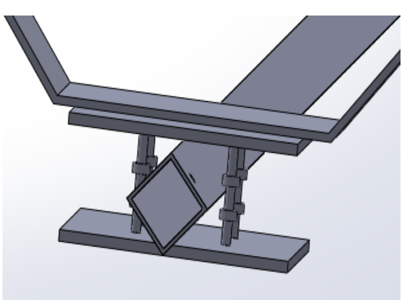

Fig. 5: Cradle & Rail Assembly

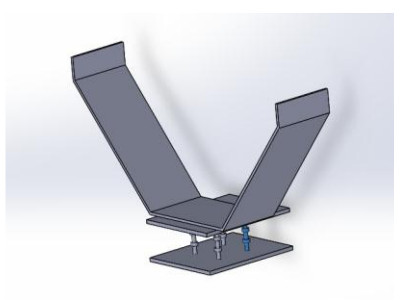

Fig. 6: Cradle Design

Fig. 7: Final Design

4. Detailed Design

Detailed design focused on finalizing the dimensions of various parts by conducting structural analysis on ABAQUS/CAE software.

4.1 Finite Element Analysis

After finalizing the design, the next step is to test the different components under their expected loading conditions. Analysis has been carried out on ABAQUS/CAE for static loading and buckling [6], on the two most important structure: Cradle and the Rail.

It has been assumed that the rigid structures in place of parts moving in the same direction as the force. One can argue that if a structure could bear the loading even under such a rigid boundary definition, the real structure would be a very reliable one.

4.1.1 Cradle

The Cradle holds the UAV in position and is that part which also accelerates the UAV up the rail. Hence the bungees are connected to the Cradle and the total bungee force of 1200 N is distributed among the two eye-hook attachment points in the base plate of the cradle.

The maximum Stress was found out to be 67 MPa which is less than the yield strength of aluminum 6063 T-6 i.e., 214 MPa. This also gave a factor of safety=3.

4.1.2 Rails

The rail is the backbone of the launcher structure. Being the longest section, it important to carry out a buckling analysis of the same. The front eye-hooks which are used to attach the bungees would transmit a load of T=1200 onto the rail and thus such a force is emulated inward through the front end of the rail. The results shown in the figure below show that the Buckling Load Factor for such a loading and an aluminum rail would be 169. This is a great result and it can be assured that the structure will withstand the loading and not buckle.

A similar fixed geometry and loading condition was used for the static analysis. It was seen that the maximum stress was 45 MPa and a maximum deflection of 1.3 mm, which is negligible. Hence the structure will withstand the loading when the bungees are kept in their fully stretched position before the trigger is pressed.

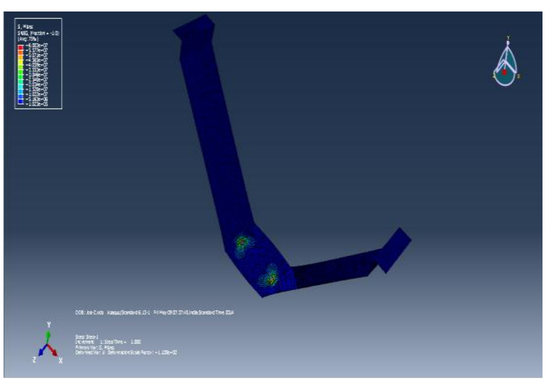

Fig. 8: Analysis of the Cradle

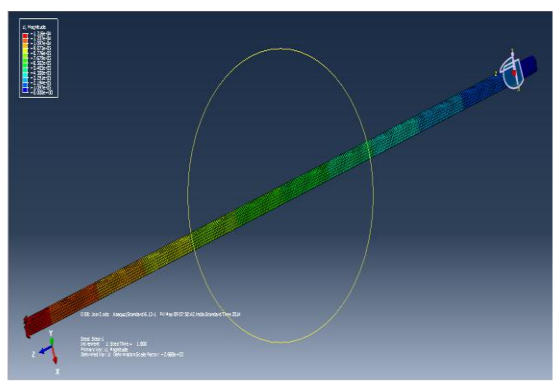

Fig. 9: Analysis of the Rail

5. Fabrication

The Rails were fabricated from three separate rectangular sections so that they can be detached for ease of transport. The three rails are joined with the help of two solid extrusions that are inserted into the rails and are finally bolted. The arms of the cradle allow a flying wing type UAV to rest in the cradle and the spacing between the arms is kept in such a manner so as to allow a 16 inch propeller to be spun by the motor before the UAV is launched. Aluminum 6063 T-6 has been used to fabricate the cradle and the rails, which allows for the whole system to be under 35 Kgs in weight. Further weight can be reduced by using Aluminum 7075 as well.

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Fig. 10: Cradle Bearing Assembly

Fig. 11: Rail Spring Latch

Fig. 12: Fabricated Cradle

6. Testing

The launcher was tested by launching a flying wing UAV and the results corroborated the values evaluated from the calculations. The launcher is triggered by pressing a lever by the operator which allows the cradle to accelerate under the influence of the bungee cord's stored potential energy.

6.1 Launch Sequence

In the below figure the launch sequence of the UAV Launcher is shown which shows one of the successful tests that was conducted. It can be seen from the figure, how the UAV is released from the launcher when the cradle reaches the end of the rail, the moment when it achieves the maximum kinetic energy.

Fig. 13: Launch Sequence

7. Conclusion

This paper demonstrates the design process involved in making a UAV launcher. First, the requirements were identified and from this, preliminary concepts ideas were generated from which a final design was chosen. The design works by mechanically winching 6 bungee cords back and simultaneously releasing them with the help of a mechanical lever type trigger. The values for parameters such as bungee stiffness, extension and aerodynamic drag were determined using the equations discussed and the MATLAB graphs. It is found that the designed bungee launcher is capable to generate force enough to launch a UAV up to 10 Kgs which has been validated by successfully launching a UAV from the same. The calculations used for estimating the bungee force requirements can hence be accepted as relevant for UAV bungee launcher and the proposed design process can be applied for designing a launcher capable of launching UAV's with higher take-off weight as well.

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