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# Structural and Kinematic Development of a Lightweight Flapping Drive System for Ornithopters

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**Abstract:** The aim of the proposed project is to develop mechanically efficient, durable and light-weight gear unit (< 2.50 gm) and flapping mechanism for an ornithopter. The light weight gear unit is to be designed and is fabricated using 3D Printer by Fusion Deposition Modelling (FDM) process. The activity involves design of gear unit and transmission mechanism, CAD modeling, design analysis through numerical simulation tools and weight reduction, rapid prototyping with fused deposition modeling, wing design and construction, components selection and procurement, experiments for evaluation of mechanical efficiency. The final deliverable is aiming to realize is an ornithopter with wingspan of 150 mm, flapping frequency of 20 Hz and overall weight of 12 gm. Ornithopters can be made to resemble birds, they could be used for military applications, such as aerial reconnaissance without alerting the enemies that they are under surveillance. Several ornithopter will be flown with video cameras on board, some of which can hover and maneuver in small spaces. With simple adaptation procedure, any ornithopter developer interested in 150 mm wingspan ornithopter, would be able to fine-tune the gear ratio and achieve optimal efficiency.

**Keywords:** Ornithopter, gear unit, weight reduction, rapid prototyping.

## 1. INTRODUCTION

An "ornithopter" is a device that imitates the flapping-wing flight of birds. The wings move independently for steering, and they can go to a level position for gliding whenever desired. In fact, you can program the wing movements any way you can imagine, to try various flight styles and aerobatic manoeuvres. It is important to understand that the record of flapping-wing devices has not been well-preserved. It is an obscure topic to begin with. The idea has been frowned upon in the field of aviation. Many of the researchers either fail to receive widespread publicity, or deliberately sequester their work. From time to time, findings of this sort still come to light. The first ornithopters were flown in France, in the 1870s. Keep in mind that this was almost a hundred years after the invention of the hot air balloon. People were looking for another way to fly, and they drew inspiration from the flight of birds. Bird flight was the example that proved a heavier-than air method of flight could exist. However, the unmanned ornithopter is a fascinating endeavour in its own right. Today, unmanned ornithopters provide an excellent educational opportunity for students, as well as great enjoyment for hobbyists. In 2007, many people witnessed what they thought were robotic dragonflies, being used by the United States government to spy on civilians. Whether or not that was the case, ornithopters can indeed be used to carry cameras and other payloads. They have been used in biological field studies, to chase birds away from airport runways, and potentially they could be used to transport various items from place to place.

## 2. LITERATURE SURVEY

Yang, L. J. and Han, H.C.,[1] in his journal explains about the light flapping air vehicle design using electrical discharge wire cutting technique. Electrical-discharge wire cutting is a promising technique that provides flexibility and lightness for a flapping micro aerial

vehicle. Electrical-discharge wire cutting is used to fabricate the high-aspect-ratio structure of the four-bar linkage gear transmission module. A new flapping micro aerial vehicle of 21.6 cm wing span consequently has a minimum body mass of 5.9 g after installing the transmission module and a flexible wing frame made of carbon fibers and polyethylene terephthalate film. This micro aerial vehicle can endure a flight time of 6 min 7 s with the wing beat frequency of 10–20 Hz. The lift and thrust coefficients of the micro aerial vehicle have been investigated through wind-tunnel testing. The proposed flapping micro aerial vehicle also exhibits the improved characteristic in the scaling law with respect to wing beat frequency versus body mass. Benjamin J. Good heart [2] in his journal explains about the history of the ornithopter: past, present, and future. Since the earliest recorded history, humans have shared a nearly universal desire for the freedom of flight. This obsession with escaping gravity's unblinking gaze to somehow slip aloft, even for a fleeting moment, has inspired many to wax poetic about the dream of flight. Looking to nature's design, man for years attempted to replicate the flight of the bird. Though science eventually shifted its focus to balloons, and then to fixed-wing flight, as a means of sustaining flight, the freedom and effortless grace of birds is as captivating now as it ever was. From the earliest days of man's dreams of launching himself skyward to today's advanced designs, flapping-wing craft, known generally as ornithopters, have held a constant place in the quest to achieve the flowing elegance of flight so easily mastered by nature's own aeronauts. In the past several years, aircraft which capitalize on the mechanics of bird flight have enjoyed a renaissance of sorts. From the recent first flight of a human-powered ornithopter, to flapping-wing designs incorporated in nano-scale unmanned vehicles, aviation design has in many ways come full circle. Aditya Tandon, AnkitVajpai, AadiNath Mishra [3] in their studies explains about the design of an autonomous ornithopter with live video reception for military surveillance. In the field of Defence and during the war of Iraq, a need for live surveillance within a close distance was felt, which lead to research of various techniques for live surveillance in the battle ground to provide the necessary intelligence to the troops in the line of action. These miniature vehicles seek to mimic small birds to achieve never before seen agility in flight. In order to better study the control of flapping wing flight they have researched and modelled a large scale ornithopter called the 'Garuda'. The 'Garuda' is capable of carrying a microcontroller, sensor package and an on board surveillance camera to transmit live video feed to the receiver in real time. The design takes special care to optimize payload capacity, crash survivability, and field repair abilities. This model has applications in the field of defence spy surveillance over enemy territories without being detected or arousing suspicion. Zachary John Jackowski [4] in his journal of design and Construction of an Autonomous Ornithopter explains about the design process of both mechanical and electrical systems of the ornithopter and initial control experiments. The design takes special care to optimize payload capacity, crash survivability and field repair abilities. He also show that it is possible to stabilize the machine in pitch with a simple PD controller through experimental testing. . Based on literature survey it is noticed that for designing of gear unit for an ornithopter, knowledge on the flapping mechanism of wings, wing structure, selection of gear ratio, design of layout of gears and mounting procedure, estimation of aerodynamic forces, selection of material for fabrication is must. The aim of this work is to reduce the weight of gear unit by adopting various mechanisms and analyze the forces on the gears. Here in this paper we selected dual crank and scotch yoke mechanisms for the gear unit. Prototypes are developed for each mechanism and thereby analysing the forces on each gear. A test was conducted on a test rig by placing the camera to observe the flapping frequency and to evaluate the forces.

### 3. TECHNICAL REQUIREMENTS IN ORNITHOPTER

#### 1. Ornithopter Power Systems

- (i). Electric Motor
- (ii). Battery

Choosing the right motor and battery are both essential for building a successful ornithopter. Here, the information regarding how to choose the right power system is provided. For typical membrane-winged ornithopters, about 100 watts per kilogram coming out of the motor should be enough power to give ornithopter a good rate of climb. As ornithopters continue to improve, it should be possible to get by on somewhat less. Estimates of the mechanical power required for bird flight vary over the range of about 10 to 50 watts per kilogram.

**Electric Motor:** For ornithopters, we want to use the "out runner" type of brushless motor. These motors have an outer casing that rotates, while the inner electromagnets remain stationary. Out runners tend to operate at a lower speed and higher torque compared with other motors. For that reason, they don't need as much gear reduction. However, if you have an ornithopter that was already designed for a high-RPM motor, you might consider using one of the regular "in runner" type brushless motors. Here a 7mm coreless motor is used

**Battery:** The battery is just as important as the motor for determining power output. There are several types of battery on the market. We probably use some type of rechargeable lithium battery in ornithopter. The most common are lithium-polymer batteries, abbreviated "Li-poly". These are in the form of rectangular foil packs, and they produce 3.7 volts per cell. Birds use their body fat to

store energy for flight. It contains seventy times more energy, for its weight, than our best batteries. That is the main reason why birds can make long distance flights, whereas battery-powered ornithopters or model airplanes typically fly for half an hour or less.

#### 4. DESIGN OF GEAR BOX

The proposed objective is to achieve a transmission unit for generating flapping motion within a weight budget of 2.5 gm. The first step towards designing the gear box is the selection of the flapping frequency to support the estimated weight of the model. Two Micro Gearboxes were developed for the project. The progress of them will be presented in parts.

- Part 1 :Dual-lever crank Gearbox
- Part 2 :Scotch-Yoke Gearbox

##### *Dual lever crank Gearbox*

A gear ratio of 25 was selected to obtain the desired frequency from the motor chosen. The wing span considered is 15 cm and the overall wing area is chosen as 60 cm<sup>2</sup>. The rpm of the motor has been safely assumed as 30000 at constant required voltage. All the gears were chosen to be of 0.3 module based on ease of availability of the micro gears.

Gear Calculations

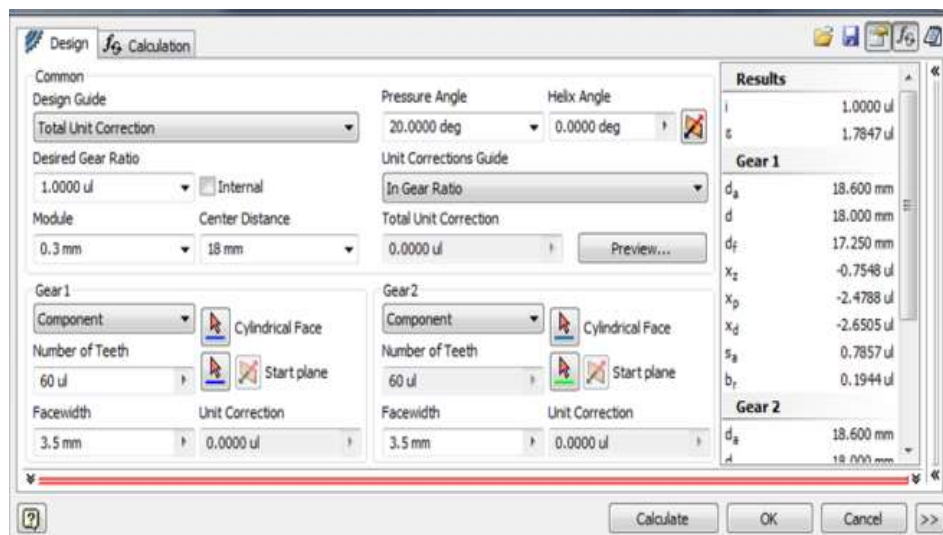


FIGURE 1.

Development of customised interface software for gear box design based on Mr Nathan Chronister, design manual 2003, Ornithopter zone (USA).

Line diagram of forces on the wing spar 1 as shown in the picture:

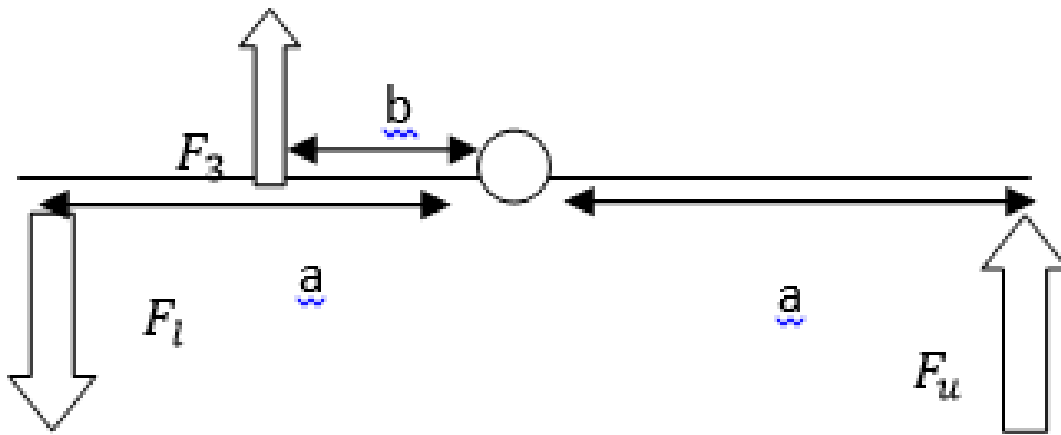


FIGURE 2.

- Since the wing span is 15 cm,  $a = 3.75$  cm
- Distance from the hinge to the wing connecting rod,
- $b = 1.2$  cm
- Assumed values of  $F_u$  and  $F_l$  for 30 gf of lift;
- $F_u = 20$  gf and  $F_l = 5$  gf.
- From moment balance,

$$F_3 * b = F_u * a + F_l * a$$

Substituting the values,  $F_3 = 78.12$  gf

For calculating the torque to be delivered by the motor, the free body diagrams of the gears are sketched.

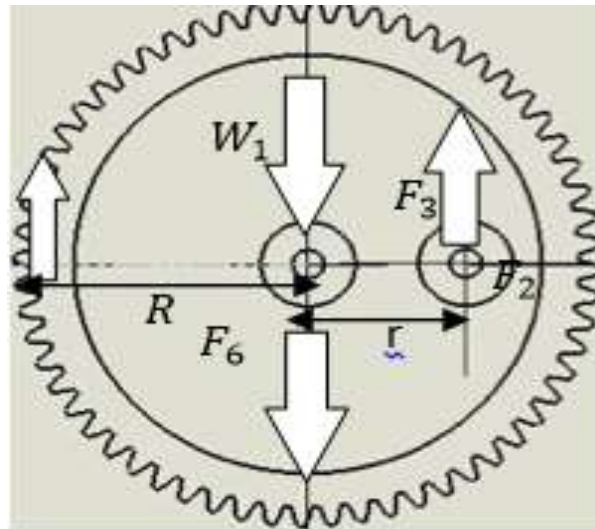


FIGURE 3.

Forces on right crank gear

- Force balance:  $F_2 + F_3 = F_6 + W_1$
- $W_1 = 0.31$  gf
- Moment Balance:  $F_3 * r = F_2 * R$
- $r = 5$  mm;  $R = 9$  mm
- $F_2 = 76 * (5/9) = 43.40277$  gf
- $F_6 = 121.217$  gf

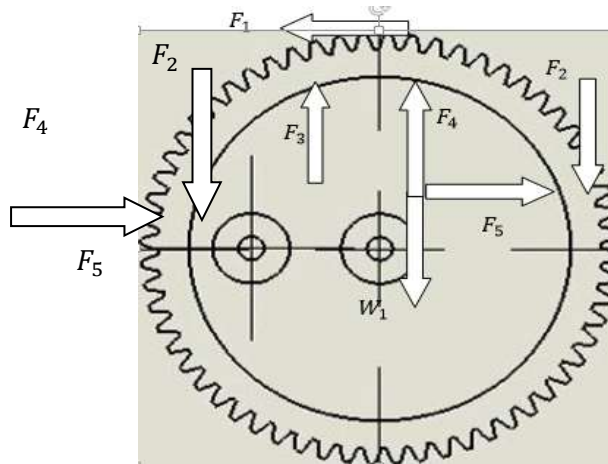


FIGURE 4.

Forces on left crank gear

Force Balance:

$$F_1 = F_5$$

$$F_3 + F_4 = F_2 + W_1$$

Moment Balance:

$$F_3 * r + F_2 * R = F_1 * R$$

$$F_1 = F_3 * \left(\frac{r}{R}\right) + F_2$$

- $F_4 = F_2 + W_1 - F_3 = -34.41233$  gf
- $F_1 = 86.8055$  gf
- $F_5 = 86.8055$  gf

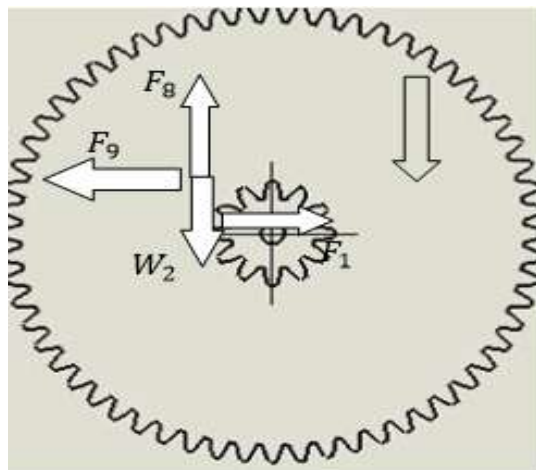


FIGURE 5.

Forces on Gear Cluster

Force Balance:

$$F_1 = F_9$$

$$F_7 + W_2 = F_8$$

Moment Balance:

$$F_1 * r_1 = F_7 * R$$

- $F_7 = F_1 * (\frac{r_1}{R})$  ( $r_1 = 1.8 \text{ mm}$  and  $R = 9 \text{ mm}$ )
- $F_7 = 17.3611 \text{ gf}$
- $F_8 = 17.5911 \text{ gf}$  ( $W_2 = 0.23 \text{ gm.}$ )
- $F_9 = 86.8055 \text{ gf}$

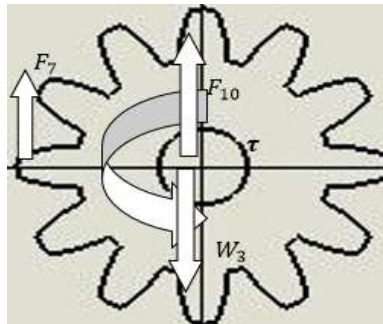


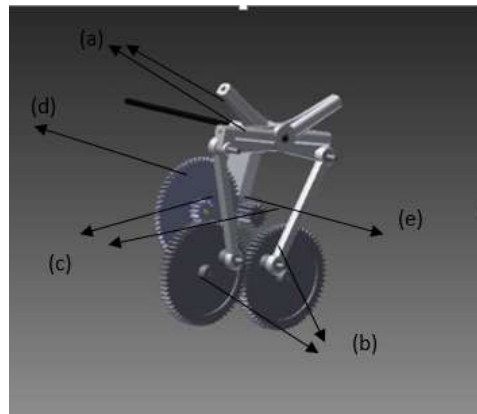
FIGURE 6.

Forces on Pinion Gear

- Force balance:  $F_7 + F_{10} = W_3$
- Moment Balance:  $F_7 * r_1 = \tau$
- $\tau = 31.24998 \text{ gf-mm}$
- $F_{10} = W_3 - F_7$
- $F_{10} = 17.3011 \text{ gf}$ ;  $W_3 = 0.06 \text{ gf}$
- Considering a flapping frequency of 20 Hz,
- RPM of motor = 30000
- Power required for motor = torque \* rpm
- Power = 0.96 W

*Development of CAD models using Gear Box:* The CAD models are developed using commercially available software to check the feasibility and the functionality of the design with the selected gear ratios and modules.

CAD design of Gearbox



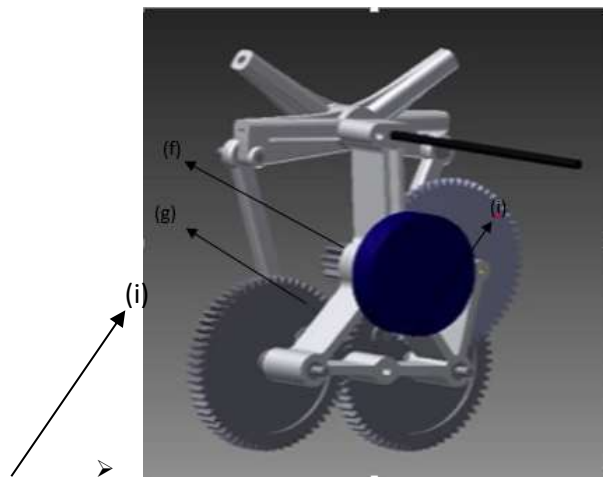


FIGURE 7.

- - Wing Holder (b) - Crank Gears
- - Connecting Rods(d) - Gear Cluster
- (e) –Pinion (f) - Brushless Motor
- (g) - Support Structure (h) - Gear Shaft
  - - Bearing
- *Numerical Analysis of the proposed design:* The weight of the gears are estimated from the CAD models developed. The force from the connecting rods is taken as 45 gm. each to accommodate the lift force of 30 gm. (= 2\*weight).
- The following images correspond to the stress analysis carried out on the individual gears. The results plotted are for the principal stresses.
- Material Properties of ABS plastic:
  - Density: 1.04 g/cc
  - Poissons Ratio: 0.380
  - Young's Modulus: 2.89 Gpa
  - Yield Strength: 40.33 Mpa
  - Ultimate Tensile Strength: 40.00 Mpa

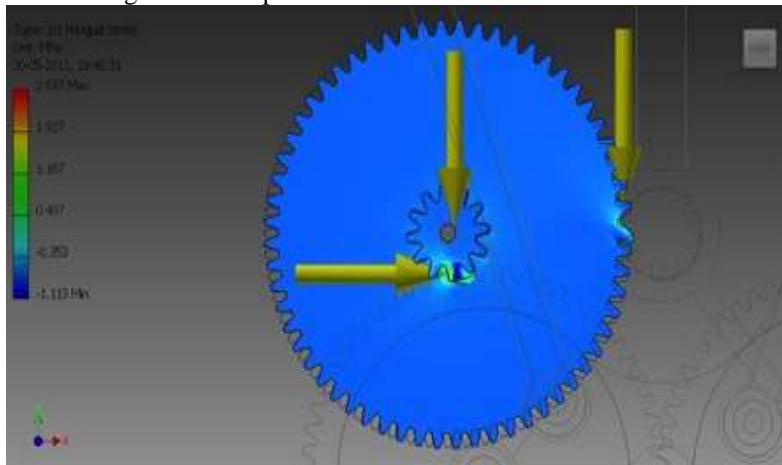


FIGURE 8. Force analysis on Gear Cluster

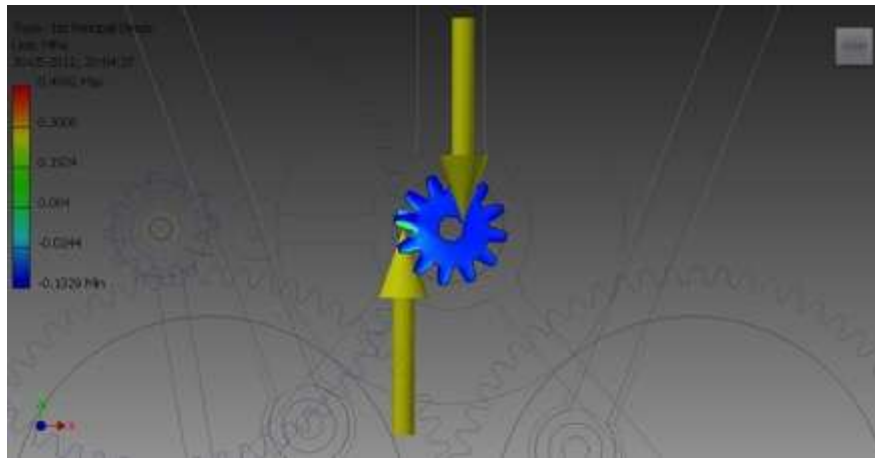


FIGURE 9. Force analysis on Pinion attached to Motor Shaft

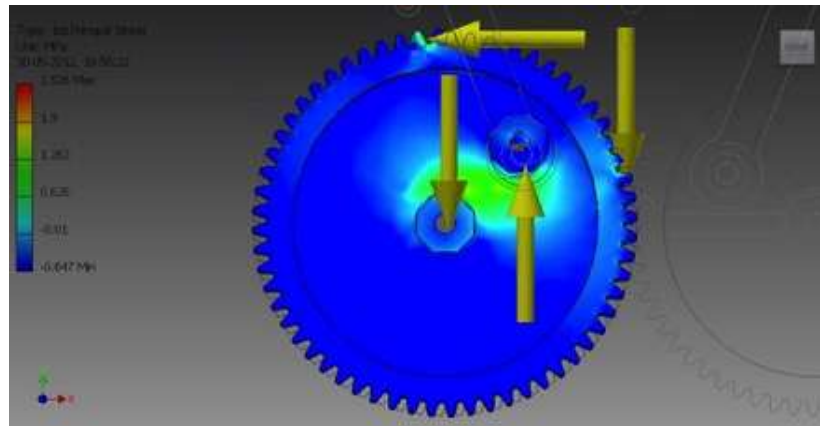


FIGURE 9. Force analysis on Left Crank Gear

The maximum stress recorded was 3 MPa which is very much less than the yield stress of the material. Therefore in the next iteration some amount of material can be removed from the gears to attain weight reduction. Further bearings will be used near the connecting rods to minimise the force transfer. The exact outcome or advantages of removal of material can be studied based on the stress analysis in a similar way as above.

### Fused Deposition Modelling manufacture- Prototype I

The initial design iteration is manufactured using the Fused Deposition Modelling technique to estimate the weight and strength characteristics of the gear box and transmission system. The material used for fabrication is ABS plastic which has a density of 1.04 g/cc. The overall weight of the transmission module arrived at is 6.5 gm. without the weight of the motor. The prototype will be helpful in analysing the areas which can be subjected to weight reduction and also in testing the functionality of the mechanism which can be the basis for the next iteration.

### Observations from Prototype I

- The gearbox weighs 6 grams, which is well above the project objective of 2.5 grams.
- The face-mounted gears have a large surface area that might drag the performance of the Ornithopter.
- FDM has been observed as a sub-optimal prototyping solution for ornithopter gearboxes due to its heavy weight. Prototyping solutions such as Micro SLA may be able to reduce the weight of the gearbox.
- 

### Prototype II- Micro SLA

The design from the Prototype I was retained and the prototyping was done by Micro SLA method which has the density of 1.03 gm/cc (Photo polymeric resin).

### Observations form Prototype II

- Chipping of the gears have been observed. Since the parts are UV cured, the fragile nature does not permit high momentum contacts. As a result, the gear chipped away at the edges preventing the gearbox from functioning.
- The gearbox weighs 4.6 grams which is still beyond the weight budget of the project.
- Lightweight mechanism like the Scotch Yoke mechanism could be used to design the flapping system to keep the weight under the upper ceiling.

### Part-I Scotch-Yoke Gearbox:

The Dual-level based gearbox utilized a multistage gear reduction principle and was relatively large. In accordance to the project objectives, a new gearbox design based on the scotch yoke mechanism was proposed. Two iterations of the gearbox have been performed in the development of the gearbox.

### Overview of Design Mechanism:

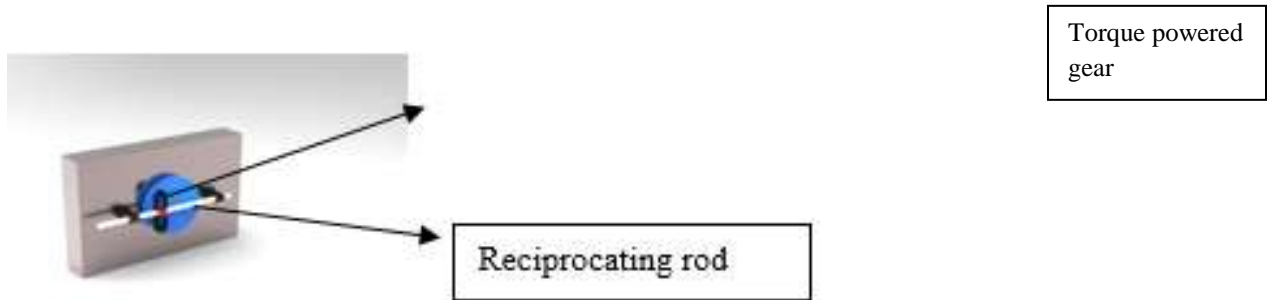


FIGURE 10.

The primary design consists of a slider that is guided by rails, while being forced to reciprocate by a torque powered gear. The reciprocating slider in turn, is attached to a lever pivoted about a point that is on the same longitudinal axis, as the pivoted point on the reciprocating slider, through a curved linkage. This makes the lever 'flap' about its pivotal point every time the gear rotates about its axis.

*Prototype III – Scotch Yoke Mechanism:* The CAD models were generated by commercially software and later converted to various formats suited for the specific manufacturing method.

**Electric Discharge Machining:** The first design iteration is manufactured using the Electric Discharge Machining technique (250 micron precision) to estimate the weight and strength characteristics of the gear box and transmission system. The material used for fabrication is Stainless steel which has a density of  $7.80 \text{ g/cm}^3$ . The overall weight of the transmission module arrived at is 1.5 gm. without the weight of the motor. The prototype will be helpful in analysing the areas which can be subjected to weight reduction and also in testing the functionality of the mechanism which can be the basis for the next iteration.

### Observations from Prototype:

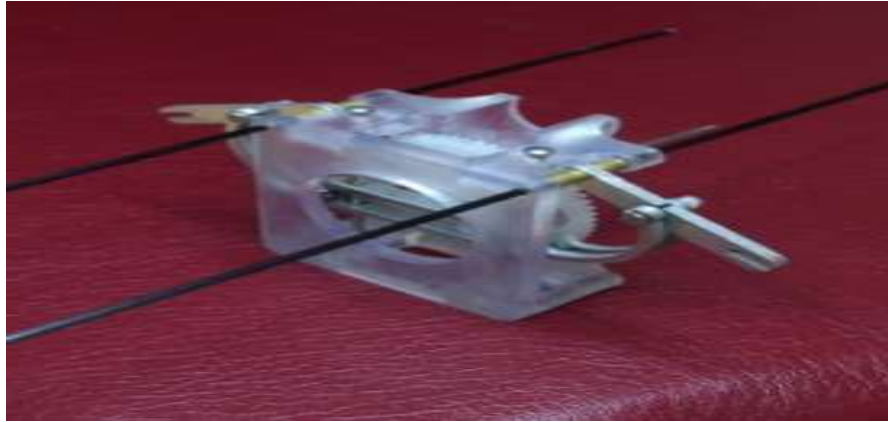
- The weight of the micro gearbox without the motor and pinion assembly is 1.5grams.
- The wing beat frequency is much higher than the Prototype-II and this mechanism designed can be preserved as it also provides sufficient torque for the ornithopter to operate with small wingspan and high wing loading.
- This prototype is not crash resistant and occasional bending is observed in the longitudinal structures of the *Base plate*. The *Base plate* needs to be redesigned and fabricated. A unibody design could replace the 6-part assembly.
- High friction levels are observed as the EDM wire-cut parts lack polish on their surfaces. Manual polish of the parts are not practical as there are tight tolerances which might result in loose structures if subjected to material removal. Despite attempts to lubricate the contact surfaces with engine oil, the resultant friction level is still above the threshold and damages the structural components of the gearbox. The slider needs to be redesigned and replaced by a component that is less susceptible to friction.

### Prototype Scotch Yoke Mechanism:

While EDM parts with extended lengths and thin joints did not perform well during the operations, smaller EDM parts have been able to take enormous loads with no apparent deformations. Certain parts like the *Wing lever*, *Coupler* were retained in the construction of the Prototype IV.

### Micro SLA fabrication of Outer casing:

To prevent the structural integrity of the Gearbox and deliver good impact resistance, MicroSLA method was chose. The image below shows the



**FIGURE 11** .Fabricated *Outer casing*.

*Observations from Prototype-IV:*

- Experimental Flapping frequency is found to be
- 22 – 24Hz
- Visualization of Figure of 8 motion achieved using high speed camera
- Performance of the gear is found to be better than the previous prototype
- Less vibration in the gear box
- Net thrust is found to be 55g

## 5. RESULTS AND DISCUSSIONS

In this study, several prototypes of the gearbox units are developed using Dual-crank lever and Scotch-Yoke mechanisms. From the observations in every prototype, another prototype is being developed using the above mentioned mechanisms. Two prototypes are developed for each mechanism. Each prototype is developed using 3D printing FDM technique. CAD models are developed using commercially available software to check the feasibility and the functionality of the design with the selected gear ratios and modules.

The static stress analysis is carried out with the calculated contact forces estimated from the free body diagrams. Force analysis is carried on gear cluster, pinion attached to motor shaft, left crank gear. The maximum stress recorded was 3MPa which is very much less than the yield stress of the material.

## 6. CONCLUSIONS

From the result of study, following conclusions can be deduced:

- The weight of the micro gearbox without the motor and pinion assembly is 1.5grams.
- Performance of the gear is found to be better.
- Less vibration in the gear box.

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