RAPID PROTOTYPING OF FLAPPING MECHANISMS FOR MONOPLANE AND BIPLANE ORNITHOPTER CONFIGURATIONS

Udayagiri Chandrasekhar[1], Lung-Jieh Yang[2], Balasubramanian Esakki[3], Subramanian Suryanarayanan[4], Sachin Salunkhe[5]

[1,4]Department of Aeronautical Engineering, Veltech Dr.RR & Dr.SR University, Avadi, Chennai-600062, Tamilnadu, India
[2]Department of Mechanical and Electromechanical Engineering, Tamkang University, Tamsui, New Taipei City-25137, Taiwan
[3,5]Department of Mechanical Engineering, Veltech Dr.RR & Dr.SR University, Avadi, Chennai-600062, Tamilnadu, India

Corresponding author: Balasubramanian Esakki, esak.bala@gmail.com

Abstract: Application of rapid prototyping (RP) techniques such as stereolithography, fused deposition modelling and selective laser sintering in the development of complex engineering systems is on upsurge due to associated functional advantages such as time-compression, design-freedom and mass-customisation. This paper examines the feasibility of using various RP techniques for fabricating light-weight flapping wing mechanisms for subsequent use in bird-mimicking micro aerial vehicles called ornithopters. These mechanisms need to fulfil conflicting set of requirements related to compactness, low weight, high transmission efficiency and adequate structural integrity. In this work, the versatility of RP techniques is leveraged for fabricating transmission shaft, linkages and gearbox housing of dual crank mechanism that powers four-winged biplane ornithopters. The fabricated mechanisms are integrated into ornithopters and tested in customised rigs. Results on RP mechanisms are compared with those of conventionally manufactured mechanisms with focus on aerodynamic performance, strength and ease of assembly. Results indicate that RP mechanisms of biplane ornithopters that weigh about 4.50 grams can sustain the flight loads during take-off, climb and landing phases. Through integration of modern direct digital manufacturing techniques into design iteration and fabrication of flapping mechanisms, the reported work opens up new vistas in the development of new generation of ornithopters.

Key words: Ornithopters, Flapping Mechanisms, Rapid Prototyping, Thermoplastics, Photopolymer

1. INTRODUCTION

Significant advancements in avionics, control systems, micro batteries, composite materials and manufacturing technologies led to widespread use of micro aerial vehicles (MAV) or drones in contemporary civil and military missions, [1]. Contribution of micromanufacturing technologies to the development of MAVs is noteworthy with reference to realization of energy efficient miniature transmission systems and brushless motors, [2]. Flapping wing aerial vehicles also called as ornithopters, merit special attention as they mimic bird flight in terms of utilizing unsteady aerodynamics at low Reynolds numbers and providing superior maneuverability, [3]. Basic purpose of a flapping mechanism is to convert rotary motion of a micro motor into the flapping motion of the wings. Regular feature of a flapping module is a four bar mechanism wherein the rotation of the crank rod leads to the movement of the connecting rod that pushes the wing up and down. In a monoplane ornithopter, two wings need to be flapped and hence two connecting rods are attached to the crank. They act at different times leading to a phase lag that in turn manifests in non-desirable asymmetric motion of the ornithopter, [4]. For overcoming this problem of asymmetry, innovative solutions such as dual cranks, transverse shaft, outboard wing hinge and staggered crank are necessitated that in turn accentuate the manufacturing complexity of ornithopter mechanisms. Many of the reported studies applied traditional fabrication techniques such as electro discharge machining (EDM) and injection moulding for fabrication of flapping mechanisms. While injection moulded parts can be successfully integrated into ornithopters [5], the fabrication process suffers from innate dependence on manufacturing of part-specific injection mould even for limited series production during developmental phase. EDM parts exhibit adequate structural integrity and accuracy but the process can handle only metals. As illustrated in some of the recent studies [6], development of ornithopters necessitates a fabrication approach that can facilitate rapid fabrication of geometrically accurate, mechanically strong and light-weight parts without any cost and time penalties especially during initial design iterations. The published literature on the application of RP techniques or additive manufacturing for development of ornithopters [7] is scarce and hence the present study addresses the need of integrating stereolithography and fused deposition modeling

(FDM) into ornithopter development. Recent studies indicate that synergistic combination of bio inspired designs, advanced manufacturing techniques and versatile sensors can lead to intelligent MAVs [8] that can lead to several unmanned missions.

2. CONVENTIONAL FABRICATION – FLAPPING MECHANISMS FOR MONOPLANE ORNITHOPTER

The authors have previously fabricated Evans flapping mechanism for application in a 20cm span monoplane ornithopter, [5]. Evans mechanism was fabricated out of Aluminium alloy Al 7075 and polyoxymethylene (POM) using EDM and injection moulding respectively. Evans mechanism consists of 11 parts including linkages, gears and load carrying frames. The resultant mechanisms are shown in Fig. 1. By changing the gear ratio from 20 to 26.67, series of characterisation tests were carried to assess torque requirement (Figure 2) at various flapping frequencies. Metallic mechanisms fabricated through EDM and plastic mechanism realised through injection moulding were found to be suitable for aerodynamic testing. But between the two options, the injection moulding was proved to be more suitable in terms of less weight and ease of assembly as indicated in table 1. The phase lag between the two cranks ideally should be close to 0^o to ensure symmetricity between the flapping of two wings. For injection moulded mechanism, the phase lag is much closer to the design intent than that of EDM mechanism. But an inherent limitation is requirement of a new injection mould (Figure 2) for each of the design iterations. Though injection process can be completed in a few minutes, the process of designing and fabricating an injection mould is significantly time-consuming and costly. Hence, for design optimisation of flapping mechanisms wherein several components need to be rapidly tried and tested, injection moulding is not an optimal option both on cost and time fronts.

Table 1. Comparison of flapping mechanisms (EDM and injection moulding)

Performance feature	Al 7075 (EDM)	POM (Injection moulding)
Weight of transmission parts (grams)	2.44	1.48
Phase lag (degree)	4.53	2.05
Assembly time (minute)	30	10
Tensile strength (MPa)	103	48

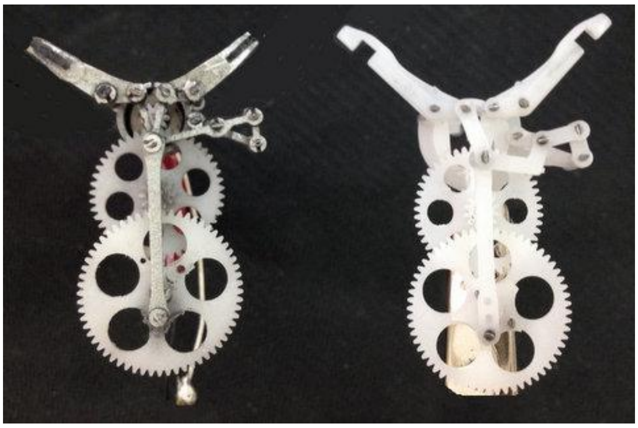


Fig. 1. Flapping mechanism fabricated through EDM (Al 7075) and injection moulding (POM)

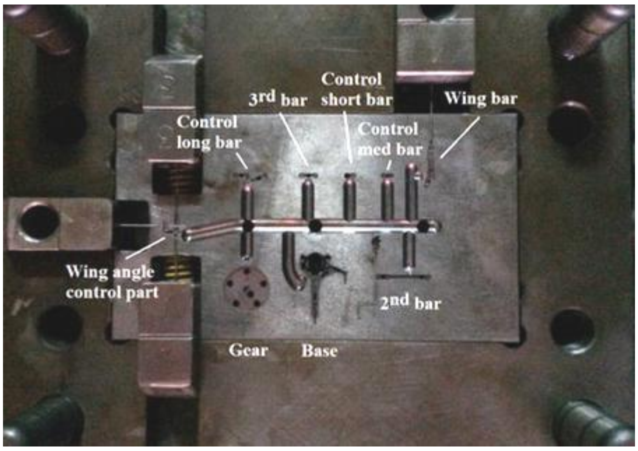


Fig. 2. Injection mould for POM components of flapping mechanism

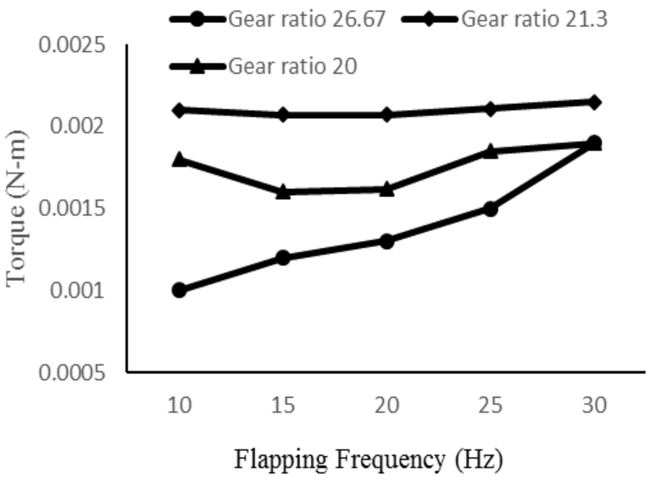


Fig. 3. Aerodynamics of monoplane ornithopters with injection moulded mechanism

3. RAPID PROTOTYPING (RP) OF BIPLANE ORNITHOPTER MECHANISM

Rapid prototyping (RP), more commonly known as 3D printing, refers to innovative manufacturing technologies that produce physical parts from digitised design data through joining or adding of material in a layer-by-layer mode. Among the various RP options, stereolithography (SLA) and fused deposition modelling (FDM) are two established techniques that produce precise plastic parts from Computer Aided Design (CAD) data through laser aided photo-polymerisation and filament extrusion respectively. Initial set of the applications related to these two technologies were largely confined to form and fit studies, as parts did not have adequate geometrical fidelity and surface finish as demanded by serious engineering applications. However, for the past few years these two processes have been able to produce prototypes with accuracy, surface integrity and repeatability levels that directly fulfil the engineering needs, [9].

In this study, the authors have taken up development of a 25 cm wingspan biplane ornithopter with a wing area of 120 cm^2 and ground speed of 2.10 m/s. Since the biplane configuration features four wings, two separate cranks or dual crank mechanism is necessitated. The dual crank mechanism consists of connecting rods, crank, gears, pinion, support frame and gear shaft (Fig. 4). These components are manufactured through stereolithography and fused deposition modelling using SLA 5510 photopolymer® and ABS P430® thermoplastic through four sequential steps of preparing of CAD data based on the design intent, pre-processing of CAD data to incorporate support features and select orientation, layered manufacturing of the parts through selection of suitable build parameters and post-processing so as to improve surface quality. In this study, CAD data is prepared through CATIA software and CAD models are converted into STL files with a chord height of 0.246 mm and control angle of 0.01 radian. STL translation errors such as missing triangles, inverted surface normal and overlapping features are removed in the pro-processing stage using Materialise Magics software.

Stereolithography parts of the mechanism are manufactured on a SL-5000 system of 3D Systems® with a 100µm layer thickness. The parts are realized by instantaneous polymerization of photopolymers through precisely guided laser beam. The scanning speed of laser beam in XY plane and laser power are so adjusted that photopolymer layers are instantaneously solidified with adequate adhesion among the layers. The challenge in photopolymerization lies in controlling the laser exposure without giving rise to excessive residual stresses. Post processing is done in a UV curing system so that polymerization process is completed. The extraneous support structures that cling to the bottom facing layers are removed in a glass bead peening system. As the intended application of stereolithography parts is accurate realization of micro mechanisms, deployment of optimized process parameters based on the reported process models [10] is one of the salient features of the present work. Process parameters such as layer spacing, hatch spacing and hatch over cure as defined in this study are deployed in fabricating the mechanism parts, leading to optimal levels of fillet features, perpendicularity, parallelism and surface roughness.

FDM parts of the dual crank mechanism are manufactured on a Fortus-250 system of Stratasys® with a layer thickness of 0.178 mm. The parts are realized through controlled extrusion of thermoplastic filaments through an extrusion head with a layer road of 0.250 mm. Orientation of the FDM parts is always done in such a manner as to keep the mating components such as gears are built with tooth profiles in xy plane. Distinct layer impressions are limited to z plane (perpendicular to build platform) and hence they do not severely affect the transmission efficiency. After completion of the build process, FDM parts are cleaned of support structures in an ultrasonic tank, [11]. Figure 4 shows the CAD data and realized FDM parts of a dual crank mechanism.

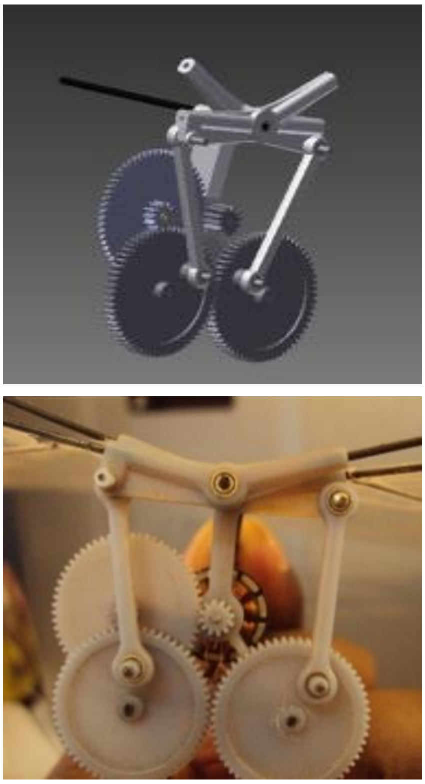


Fig. 4. CAD model and FDM prototype of dual crank mechanism

4. TESTING OF RAPID PROTOTYPES

FDM and stereolithography parts are scanned using an ARTEC® 3D scanner for evaluating the dimensional fidelity of the parts with reference to CAD data. The parts are assembled and fitted into a four-winged biplane ornithopter with overall wing surface of 120 cm^2. Figure 5 shows an assembled ornithopter with FDM mechanism. Biplane ornithopters with FDM and stereolithography mechanisms are tested on a static test rig for experimental evaluation of phase lag, thrust characteristics, flapping frequency and torque requirements. The customised test rig shown in Figure 6 is also prototyped used stereolithography as the commercial rigs are not found suitable for aerodynamic testing of miniature aerial vehicles. The load cells are integrated into the test rig and thrust forces are measured for SLA and FDM based ornithopters. It is observed from Figure 7a that, FDM mechanism achieved maximum thrust of 70g in comparison with SLA mechanism. Figure 7b shows the flapping frequency at various motor speeds expressed in terms of % of duty cycles. The phase lag of both the mechanisms is less than 2.30° which is comparable to that of injection moulded modules. Further, field tests on biplane ornithopters reveal that these mechanisms successfully withstand the flight loads during take-off, cruise and landing that confirms the adequacy of part strength. Stereolithography turns out to be the marginally better option of the two RP options in terms of dimensional accuracy, build time and post cure strength. However, stereolithography parts are found to relatively more brittle and sharply defined features in these parts are susceptible to chipping during assembly and testing procedures.

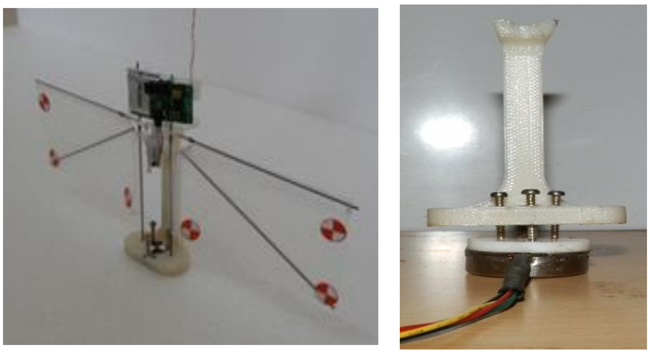
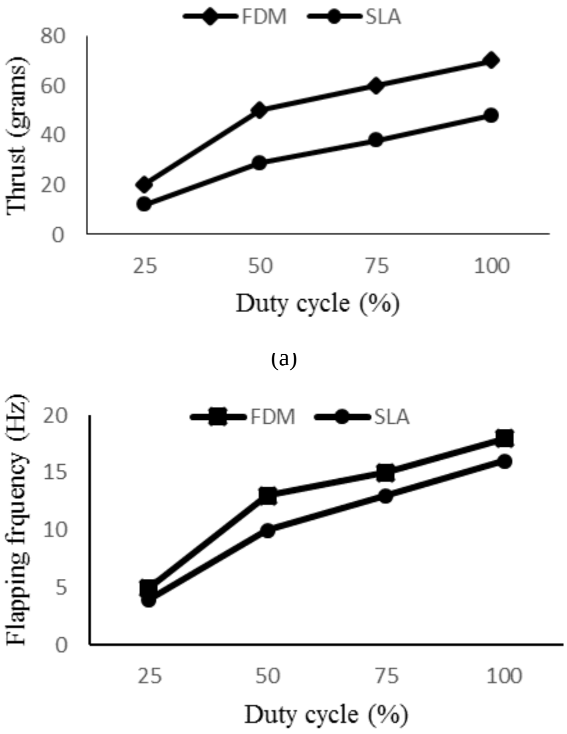


Fig. 5. FDM mechanism in a biplane ornithopter

Fig. 6. Rapid prototyped test rig

Table 2. Performance comparison of SLA and FDM mechanisms assembly

Performance Feature	SLA	FDM
Weight - transmission parts (grams)	4.52	4.23
Phase lag (°)	2.28	2.24
Assembly time (minutes)	18	18
Post cured tensile strength (MPa)	72	33
Dimensional fidelity (±μm)	22	34
Estimated time for new prototyping (hours) inclusive of part building, pre and post processing	14	20



(a)

(b)

Fig. 7. Aerodynamic characterization of biplane ornithopters (RP dual crank mechanisms)

5. CONCLUSIONS

Flapping mechanisms are fabricated out of ABS and epoxy resin based photopolymer through RP techniques of FDM and stereolithography respectively for use in biplane ornithopter. These RP mechanisms are tested with reference to mechanical and aerodynamic functionalities. These tests indicate that dimensional integrity, resultant phase lag, flapping angle and assembly time of RP mechanisms are comparable to outcomes of traditional injection moulding and EDM. Field trials demonstrate adequate mechanical strength of RP mechanisms to withstand flight loads during different take-off, cruise and landing modes. Cycle time for a new design iteration based on RP options is substantially less than that of traditional options. More importantly, RP based fabrication allows numerous design iterations without time penalty due to which mechanisms can be optimised to achieve compact and light-weight configurations with beneficiary impact on manoeuvrability and endurance of ornithopter missions.

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