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Topology optimization of transmission system of flapping-wing micro aerial vehicle via 3D printing

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Abstract. 3D printing makes the manufacturing of complex and small structures more convenient, which has promoted the development of flapping-wing micro aerial vehicle (FMAV) in recent years. And structural reliability and weight play decisive role in service life and endurance of FMAV transmission system. Though topology optimization design is conducive to obtain a light-weight structure, current researches still lack guidance of considering non-linear factors of 3D printing material. In this paper, experiment as well as numerical computation efforts was acted in concert to gain a reliable topology optimization method. A numerical computation model describing the mechanical behavior of FMAV transmission structure was established and verified by experiments. And then topology optimization modeling method considering non-linear factors was presented and optimization results were verified by dynamic simulation and experiments. Detail comparison of different optimized results based on different load status was carried out to explore the leading factors affecting the optimization results. Engineering guidance for transmission system lightweight design of FMAV with better fatigue resistance was given, which may shed lights on light-weight design for future advanced FMAV.

1. Introduction

The development of 3D printing technology makes the manufacturing of FMAV more convenient. In recent years, FMAV design has become a heated topic and scientists and engineers have explored FMAVs with different linkage-based transmission systems manufactured by 3D printing [1-3]. Lightweight design can effectively extend its endurance time, while engineering experience alone is difficult to obtain light-weight structure simultaneously meets the requirements for strength.

Extensive researches have been carried out for topology optimization of additive manufacturing. Siva Rama Krishna et al. [4] demonstrates the effectiveness of the SIMP technique of Topology Optimization for Additive manufacturing through FEA solver package Altair Optistruct 12.0. And Wook-han Choi et al. [5] investigated and evaluated three representative commercial structural optimization software systems such as Genesis, MSC Nastran and OptiStruct by solving various test examples in different scales, and they concluded that OptiStruct gives excellent optimum solutions in structural topology optimization.

The above works indeed provided significant guidance for structural topology optimization; while it is still lack of guidance of considering nonlinear factors of 3D printing material when carry out topology optimization, especially for the tiny FMAV transmission system, which exists nonlinear contact behaviors during the process of flapping. In this paper, topology optimization modeling method considering non-linear factors were presented and optimization results are verified by dynamic simulation and experiments. Detail discussions were carried out to explore the leading factors affecting the optimization results.

2. Model and Material

2.1. *Transmission System Model*

The transmission system model is shown in Fig. 1. The reduction ratio of the gear system is 18 and the flapping amplitude design value is 120°. All parts are manufactured by 3D printing using Ultraviolet (UV) Cureable Resin except for the gears, and we adopted standard engineering plastic gears with module of 0.5. Components are connected by aluminum or copper rivets.

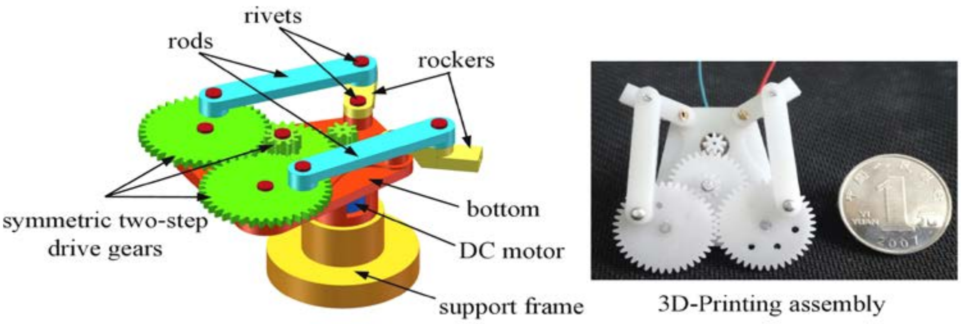

Figure 1. Structure illustration of FMAV transmission system

2.2. *Material Constitutive*

Ultraviolet (UV) Cureable Resin was chosen to fabricate the components of transmission structure. It can be polymerized at a certain wavelength (250-300 nm) of ultraviolet light and solidifying. The 3D printing specimens using UV Cureable Resin has a tensile strength range from 45MPa to 50MPa, and the density is about 1.1g/cm3. Comprehensive mechanical behavior of this material was characterized and analyzed in [6]. The constitutive behavior of UV curable resin was equivalent to numerical model using *MAT_PIECEWISE_LINEAR_PLASTICITY material model in LS-DYNA [7].

3. Method and Modeling

3.1. *Dynamic Simulation Modeling*

Solid 164 unit [7] is selected to build the FE model of 3D-printing components and the plastic gears. The spar of flapping wing is equivalent into an uniform beam with a length of 90mm to simulate the effect of inertia of flapping wing. The total amount of solid finite element units is 46,083, as shown in Fig. 2. In addition to gears and rivets, the other components of the transmission system were fabricated via 3D printing using UV curable resin. The gears and rivets were defined by *MAT_RIGID model [7], and the specific material parameters are listed in Table 1, where E donates the Young's module, ρ represents the density, ν is the Poisson's ratio.

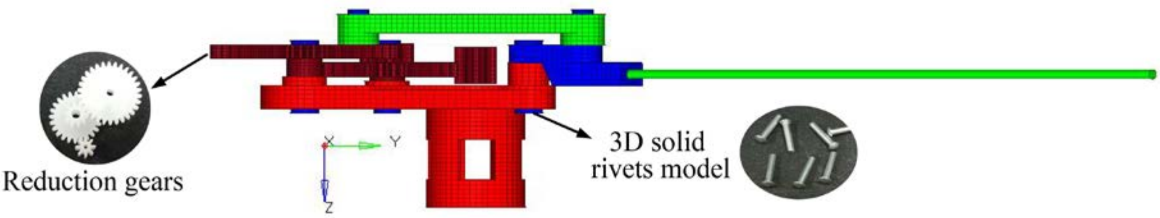

Figure 2. Finite element model of FAMV transmission system

Table 1. Material parameters of rigid parts

	E(MPa)	(g/cm^3)	
Copper rivets	90,000	8.90	0.3
Aluminum rivets	70,000	2.70	0.3
Motors	100,000	4.58	0.3
Plastic gears	2,062	1.20	0.3

The diagrammatic sketch of the boundary conditions of the transmission system is shown in Fig. 3. The lift force and drag force acting on flapping wings are equivalent to two sets of shear force and moment loaded on the flapping rod. The aerodynamic lift is obtained from lift test platform [8], and the lift test is also used as an assessment method of structural strength evaluation. To simulate the situation on the lift test platform, a constant rotation angular velocity around the Y-axis of the global coordinate system is assigned to the first-stage gear, and the bottom of the support frame is constrained in all directions.

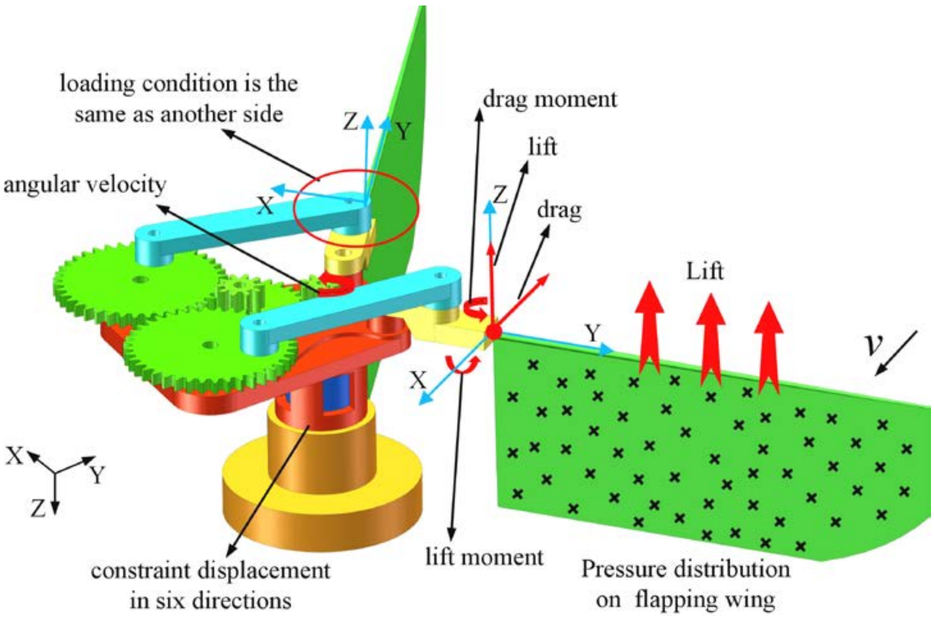

Figure 3. Illustration of boundary conditions

3.2. Topology Optimization Modeling

The structural weight of bottom accounts for 49.36% of the transmission system, which means that it has bigger space for topology optimization. The walls of each hole of the bottom are set as non-design zone, and the rest parts are set as design zone, as shown in Fig. 4. Define the material attribute of the bottom as solid isotropic material and carry out a density-based topology optimization design through Altair Optistruct 17.0. The loads of rivet holes at certain moments in a movement cycle are obtained as load statuses of topology optimization. Response function of volume, static stress and displacement is defined. A draft direction perpendicular to the upper surface of bottom is set to ensure the smoothness of mounting surface. We define the volume objective function to minimizing the volume as the optimization goal for each topology optimization case. Based on the dynamic simulation results under the frequency of 30Hz, states with resultant force (depicted as $F_{R,Max}$) of the rivet holes more than 120N are chosen; states with edge deformation (depicted as $D_{Z,Max}$) exceeding 0.2mm are chosen;

states with the maximum Von Mises (depicted as $\sigma_{Von,Max}$) exceeding 20Mpa are selected. Topology optimization design of the bottom based on $F_{R,Max}$, $D_{Z,Max}$ and $\sigma_{Von,Max}$ are carried out respectively.

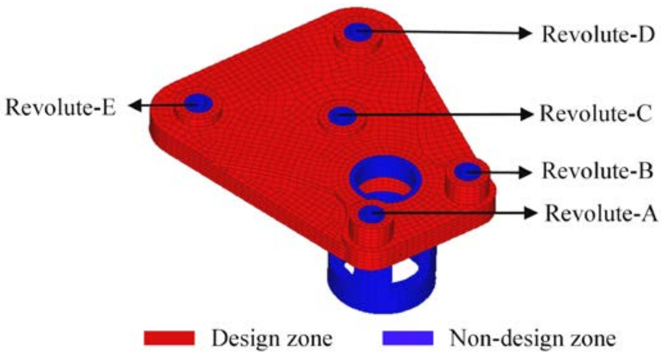

Figure 4. Topology optimization model of bottom

4. Results

4.1. Motion

The motions of FMAV under the frequency of 30 Hz were recorded by high-speed camera. The flapping angle amplitude increased by about 13 degrees after installing flapping wings and this phenomenon were predicted by the FE model, as shown in Figs. 5. When flapping with wings, linking rods are influenced by the inertia, centrifugal force, and aerodynamic forces together. These forces might intensify the gap effect between the rivets and holes, leading to an increase of flapping amplitude. The load definition of the FE model is thus verified.

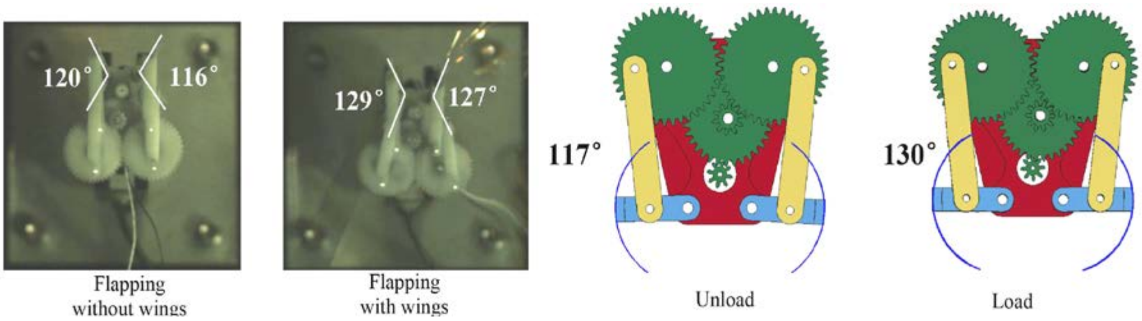

Figure 5. Comparison of the flapping amplitudes of actual transmission structure and FE Model

4.2. Structural Strength

The strength limit of UV Cureable Resin is taken as failure criterion to analyze the structural integrity of the transmission structure. We obtained the distribution of dangerous states of each component, as shown in Fig. 6. The $\sigma_{Von,Max}$ of each component is lower than the tensile strength limit (i.e., 49 MPa) of the UV Cureable Resin, which meets the requirement of structural strength. The $\sigma_{Von,Max}$ of bottom is 25.9Mpa and no large shear stress occurs. It indicates that there is enough space for conducting topology optimization for the bottom.

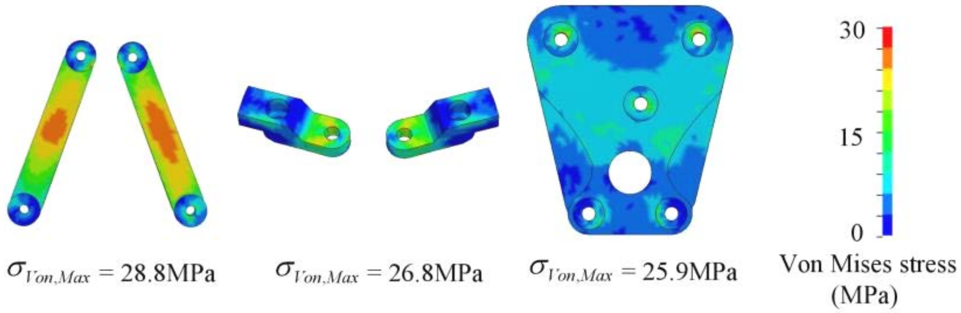

Figure 6. Dangerous states of structural strength of transmission system

4.3. *Topology Optimization Results*

The distribution of material density coefficient of optimization results is shown in Fig. 7. It can be seen that the load transfer path based on each load status selection method is quite different. The optimization result based on $F_{R,Max}$ is similar to that of the result based on $\sigma_{Von,Max}$. Weight reduction ratio of the result based on $F_{R,Max}$ is the least. Preliminarily speculating, the optimization process based on $F_{R,Max}$ is to retain enough weight to resist large deformation and meet the stress constraint. The load transfer path of the optimized bottom based on $D_{Z,Max}$ has a larger distribution area than the others. The material distribution area is retained as far as possible in the optimized result based on $D_{Z,Max}$, so as to disperse the shear force generated by the vibration deformation of Z-direction.

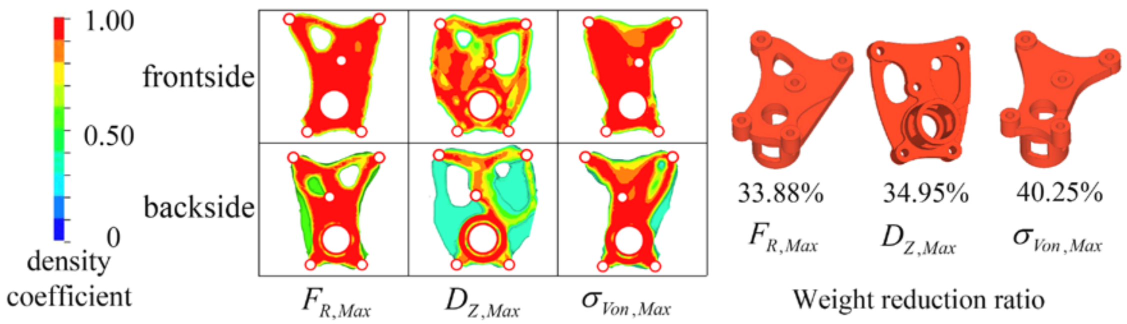

Figure 7. Topology optimization results of bottom based on different load status

The distribution of dangerous states of different bottoms is shown in Fig. 8. It can be seen that the of all optimized bottoms are smaller than the tensile strength limit. The $\sigma_{Von,Max}$ of the optimized bottom based on the $F_{R,Max}$ is the least, which corroborates the speculation above that retaining enough weight is to resist large deformation energy. The stress value of optimized bottom based on $D_{Z,Max}$ is well-distributed, which indicates that a larger coverage area helps to reduce bending deformation to resist shear failure. Table 2 shows the comparison of various optimized bottoms. In summary, selecting load statuses for topology optimization based on the resultant force make sense to reduce the maximum stress value, based on the maximum stress states can achieve a better weight reduction effect, and based on the bending deformation helps to disperse shear stress and improve the ability to resist bending deformation.

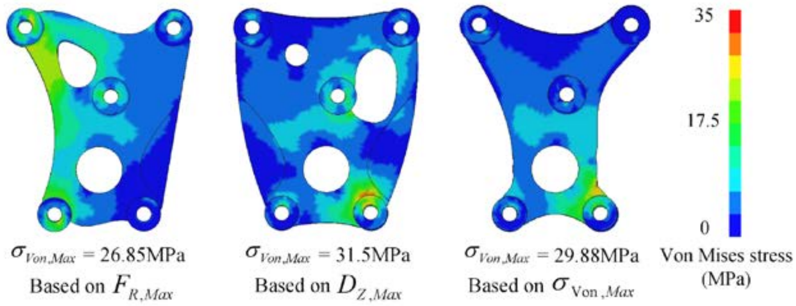

Figure 8. Topology optimization results of bottom based on different load status selection methods.

Table 2. Parameter comparison of different optimized bottoms

	Based on $F_{R,Max}$	Based on $D_{Z,Max}$	Based on $\sigma_{Von,Max}$	Original bottom
Maximum Von Mises stress	26.85MPa	31.5MPa	29.88MPa	25.90MPa
Maximum Z-displacement	0.58mm	0.50mm	0.58mm	0.38mm
Weight reduction ratio	33.88%	34.95%	40.25%	/

5. Summary

In this paper, we present a numerical computation modeling method describing the mechanical behavior of FMAV transmission structure based on the constitutive model of Ultraviolet(UV) Cureable Resin and nonlinear dynamic characteristics, and the reliability of this dynamic simulation model is verified by comparing the motions and stress value with experimental measured value. Topology optimization of bottom based on the dynamic simulation results is carried out, and the difference of optimization results based on different load conditions is discussed in detail to find out the leading factors of the optimized results. And all the optimized results are verified by the dynamic simulation model again. Engineering guidance for transmission system lightweight design with better fatigue resistance toward FMAV transmission system via 3D printing drawn from this article are as follow:

1. The results obtained from topology optimization of each component should be evaluated by dynamic simulation again, so as to verify the structural strength through complex nonlinear behaviors of actual states which static analysis does not cover.
2. Selecting load statuses for topology optimization based on the resultant force make sense to improve the ability to resist deformable energy and reduce the maximum stress value.
3. Selecting load statuses for topology optimization based on the maximum stress states can achieve a better weight reduction effect.
4. Selecting load statuses for topology optimization based on the bending deformation helps to disperse shear stress and improve the ability to resist bending deformation.

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