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Structural integrity analysis of transmission structure in flapping-wing micro aerial vehicle via 3D printing

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ABSTRACT

3D printing makes the small and compact transmission system of flapping-wing micro aerial vehicle (FMAV) available for in-house designs and tests. However, the high flapping frequency requiring stringent strength integrity and fatigue longevity for the structure itself always serves as the major responsible reason for the structural failure of FMAV. In this paper, experiment as well as numerical computation efforts were acted in concert to gain an insightful understanding of the failure mechanism for the transmission structure of FMAV. Firstly, a FMAV structure was fabricated by 3D printing using Ultraviolet(UV) Cureable Resin. The isotropic constitutive behavior of the resin was evaluated and confirmed. Further, numerical computation model describing the mechanical behavior of FMAV structure was established and verified by experiments. Secondly, together with the computational structural model and constitutive model, the dynamic response of the transmission structure subject to high frequency flipping motion was described. Both simulation and experiments share the same failure mode and configuration and the dominate factor for the failure was found out to be the excessive bending deformation. Finally, design parametric study along with different boundary conditions aiming at the future ground testing were conducted to uncover the governing influences over the transmission structure integrity. Results may shed lights on the structural integrity design of FMAV and pave a new road for future advanced FMAV design, manufacturing and testing.

1. Introduction

Flapping-wing micro aerial vehicle (FMAV) is a new type of aircraft by mimicking the flying behavior to that of small birds or insects. Comparing to the traditional fixed wing or rotor-type aircraft, FMAV only needs to control the motion of flapping wings, by changing the size and direction of lift to control the flight attitude [1,2]. Therefore, its transmission system should be designed very compact. In recent years, FMAV design has become a heated topic and scientists and engineers have explored FMAVs with different transmission systems. The main forms of FMAV transmission systems at present are linkage-based [3–6], string-based [7,8] and electromagnet-based [9–11]. Linkage-based transmission system has a satisfactory transmission efficiency and the motion of flapping wings can be controlled by a flexible structure. Due to the complicated geometric shape and configuration, 3D printing becomes an effect fabricating method for such a complex structure. The structural integrity subject to quasi-static load bearing check is satisfactory while under the high flapping frequency, the wing mounts, links, and push rods fabricated by 3D printing would wear and occasionally fail over the time [8]. Maintaining the structural integrity of transmission structure is of great significance to ensure the

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service life.

Extensive research has been carried out for motion smoothness and structural strength design of planar linkage mechanisms. Multi-body dynamics simulation is usually used to analyze the dynamic characteristics of traditional industrial linkage mechanisms, such as cranes, robotic arms, and engine crank mechanisms, etc. A.A. Shabana et al. put forward a deformable multibody dynamics method to determine the actual reaction forces at the joints [12,13]. D. Surdilović et al. established a general approach to analysis the flexible mechanical system concerning kineto-elastodynamic effects [14]. S.M. Varedi et al. [15] and L.X. Xu et al. [16] investigated revolute joints with clearances and friction, and set up dynamic analysis models to estimate the impact and contact forces.

The above work indeed provided significant guidance for the structural durability design of mechanical systems. While it is difficult to build a reliably rigid-flexible coupling dynamics model, and the particularity of transmission structure of FMAV fabricated by 3D printing lies in the nonlinear and elastic deformation of materials. H. Kim et al. [17] and F. Wang et al. [18] carried out experimental study on acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) respectively, and their results both shared that these two kinds of 3D printing materials had the characteristics of anisotropy and with a low strength limit. Y.T. Kao et al. [19,20] carried out experimental study and finite element analysis of bi-material structure(BMS) and concluded that the non-linear elastic transition and crack-induced are the leading factors contributed to the rapid structural rupture. In summary, the structural integrity analysis for the transmission structure is lacking in available references.

To bridge the gap, therefore, in this paper, a numerical computation model describing the mechanical behavior of FMAV transmission structure was established and verified by experiments. Detail discussions of governing factors of FMAV structural integrity were conducted to reveal structural failure mechanism of 3D printed linkage system in FMAV. Finally, engineering design guidance for transmission stronger system design of FMAV with better fatigue resistance was also given.

2. Transmission system sample preparation

2.1. Material

Reference [21] introduced six widely used materials in the field of 3D printing, and there are mainly four kinds of printing materials in morphology, which are liquid photosensitive resin, plastic film, low melting point wire material and powder material. Considering the weight and structural reliability of FMAV, e.g. density, structural strength, wear resistance, thermal stability and surface accuracy, Ultraviolet(UV) Cureable Resin [22] 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 45 MPa to 50 MPa, and the density is about 1.1 g/cm3. Comprehensive mechanical behavior of this material is characterized and analyzed in Section 3.1

2.2. Structure illustration

As shown in Fig. 1(a), the transmission system was composed of a two-stage reduction gear system, a support frame, and two four-bar linkages symmetrically arranged on the support frame. The reduction ratio for the gear system was 10.5, and an 8520 coreless DC motor was used to drive the gear system. Flexible flapping wings were installed in the central hole of the flapping rod, and the flapping amplitude design value was 120°. All parts were 3D printed by UV Curable Resin except for the gears, and we adopted standard engineering plastic gears with module of 0.5. Components were connected by aluminum or copper rivets and the assembly is shown in Fig. 1(b).

3. Methodology

3.1. Material characterization and constitutive modeling

To gain a comprehensive understanding, a uniaxial tensile testing was conducted. The specimens were fabricated by 3D printing using UV Cureable Resin according to ASTM standard D638–14 [23] and tensile tests was performed. Loading speed was set as 2 mm/min with three repeated tests. The ratio of the tensile load to the cross-sectional area of the specimen is stress, and the ratio of the displacement of the clamp to the initial length of the specimen is strain. Fig. 2 shows the experimental stress-strain curves and all tests agreed well. Typical constitutive behavior showed that initially, the stress increased with the deformation nonlinearly until the peak value. Then, plastic deformation occurred until the sample broke at the failure strain.

For engineering analysis, a Ramberg–Osgood model is used to describe the nonlinear elastic section [24,25], and the plastic softening section can be described by Mazars damage model [26,27]. Ramberg and Osgood presented the following equation as follows:

$$\varepsilon = \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^{n} \tag{1}$$

where ε denotes strain, σ represents stress, E denotes Young's modulus, K is the intensity coefficient, and n is the strain hardening coefficient; K and n parameters are related to the material hardening degree. A new parameter α, whose value is related to K is defined as follow: