FIRST PROTOTYPE OF POLYMER MICROMACHINED FLAPPING WING NANO AIR VEHICLE

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ABSTRACT

The novelty of this study includes the development of an insect-inspired flapping wing nano air vehicle (FWNAV) using polymer micromachining or MEMS flyer and its computational flight performance using a fluid-structure interaction (FSI) analysis. The present FWNAV consists of a micro transmission with a support frame, a micro wing, and a piezoelectric bimorph actuator. This FWNAV can be easily fabricated using polymer micromachining and its flight performance can be accurately predicted using the FSI analysis. Hence, this study will lead toward the development of tethered and flyable FWNAVs with the size of the smallest flying natural insects.

KEYWORDS

MEMS flyer, flapping wing nano air vehicle, insect-inspired, flight performance, fluid-structure interaction, polymer micromachining.

INTRODUCTION

Insects have evolved sophisticated flight maneuverability and hovering using flapping wings [1], so many researchers have been developing flapping wing nano air vehicles (FWNAVs) for applications such as earthquake disaster management [2]. However, none of them have developed FWNAVs with a minimum insect size of about 1mm. Most recently, a few researchers have developed the FWNAVs with a size of about a few cm [3-5] and they produce enough lift-to-drag ratio for hovering [3,5], but their further miniaturization is difficult, because of the complicated fabrication process and the post-assembly. The development of FWNAVs at the insect scale has two difficulties; the primary issue is the design difficulty because of strongly coupled multi-physics like electro aeromechanical coupling coming from scale effects [6,7], and the secondary issue is the fabrication and assembly of components. The design difficulties can be overcome by a design window search methodology [8] where a design solution will satisfy all the design requirements while fabrication difficulty can be overcome by the microfabrication method [9].

We have developed the 2.5-D micro-transmissions for FWNAVs to produce the desired flapping motion transmitted from a small bending displacement of the piezoelectric bimorph actuator [9-11]. The 2.5-D structure induces ease in miniaturization and no post-assembly. In the development, we demonstrated the design of a 2.5-dimensional FWNAV using an iterative design window search method to solve the design difficulty [12,13].

We also demonstrated that the computational fluid-structure interaction (FSI) analyses can be used for the accurate estimation of the flight performance of the FWNAV because of the strong coupling between the flapping wings and the surrounding air [7, 14, 15].

Figure 1 shows the conceptual view of a polymer micromachined FWNAV which consists of a micro-transmission, a pair of the micro wing, and a piezoelectric bimorph actuator. This study presented a prototype of this FWNAV, and its computational flight performance was evaluated using nonlinear structural dynamic and FSI analyses. Since our FWNAV has a 2.5-dimensional structure that can be easily fabricated using polymer micromachining, this study will lead to the further miniaturization of FWNAVs equivalent to the smallest natural insects.

FLAPPING WING NANO AIR VEHICLE

Figure 2 shows the design of the first prototype of a polymer micromachined FWNAV in plan and sectional views, indicating that micro transmission is a central and essential component to get the desired flapping motion whereas a pair of micro wings exerts the flight simulation of the FWNAV. Our FWNAV was designed using the iterative design window search methodology where conflicting design requirements, nonlinear and unsteady were being satisfied [13]. The development of our FWNAV has been carried out in two steps: (1) The fabrication of micro-transmission and micro-wing, and (2) the assembly of these components along with the bimorph actuator. In our previous study [11], we proved that our polymer micromachining process is feasible for the fabrication of this kind of structure, since the dimensional precision of the fabricated one compared to the design was very high about 75% and the static performance error between the experiment and numerical was about 10% only.

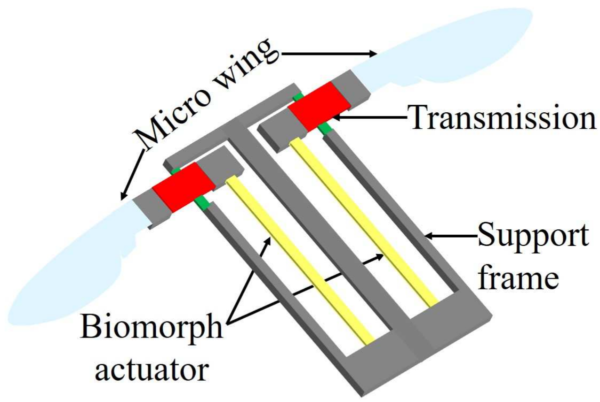

Figure 1: Concept of polymer micromachined flapping wing nano air vehicle or MEMS flyer.

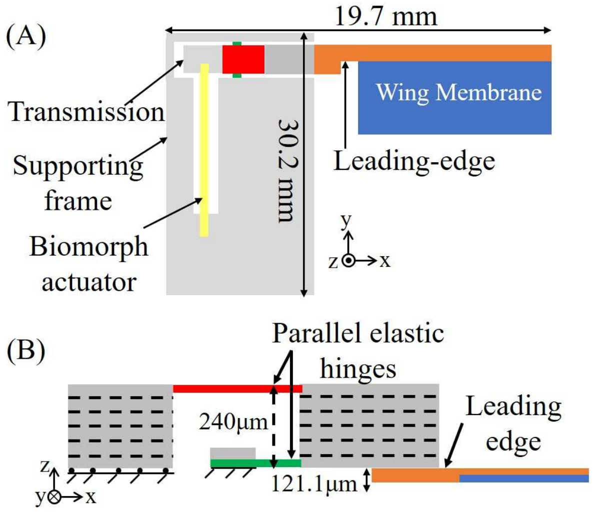

Figure 2: Actual design of FWNAV in plan (A) and section views (B). Note: Figures are the best views in color prints.

Transmission

In our FWNAV, the transmission is a key component and it has a 2.5-dimensional structure. It transduces the small translational displacement of the bimorph actuator into the large rotational displacement using the simple cantilever bending mechanism [9]. Initially, it was designed using nonlinear static analysis, and later it was designed using nonlinear dynamic analysis and it was observed that the stroke angle is also increasing from 40° to 60° due to the inertial effect. The transmission with the supporting frame is fabricated using standard microfabrication steps: the lamination, the exposure, the development, and the curing process [9–11]. Polyimide adhesive sheets with a thickness of 40μm are used as a material for microfabrication.

Micro Wing

The micro wing of our FWNAV is initially designed using the morphological and kinematic parameters of dipteran insects. Later its detailed design is done using the linear static stress analysis and mass of micro wing flapped by the transmission. It is also fabricated using the standard microfabrication steps and polyimide materials, of which material properties are given in Table 1.

Figure 3 shows the developed first prototype of the polymer micromachined FWNAV. The numerical mass (density × volume) of the transmission, micro wing, and FWNAV are respectively 76.30mg, 1.88mg, and 467.18mg because the actuator's mass is 289mg.

NUMERICAL FSI ANALYSIS

In the numerical FSI analysis, the coupled physics between the flapping wings and the surrounding air is incorporated by solving the following equations: an incompressible Navier-Stokes equation for the fluid (the ALE method is used), the equation of motion for the elastic body (the total Lagrangian method is used), and the coupled conditions on the fluid-structure interface are solved using the projection method [14]. These equations are discretized using the finite element method, and the monolithic equation system for the FSI can be obtained in the matrix-vector form as follows:

$$ {}_{L}\mathbf{M}\mathbf{a} + \mathbf{C}\mathbf{v} + \mathbf{N} + \mathbf{q}(\mathbf{u}) - \mathbf{G}\mathbf{p} = \mathbf{g}, \quad (1) $$

$$ {}_{\tau}\mathbf{G}\mathbf{v} = \mathbf{0}, \quad (2) $$

where **M**, **C**, and **G** denote the mass, diffusive, and divergence operator matrices, respectively, and **N**, **q**, **g**, **a**, **v**, **u**, and **p** denote the convective term, elastic internal force, external force, acceleration, velocity, displacement, and pressure vectors, respectively, and the sub-scripts L and τ indicate the lumping of the matrix and the transpose of the matrix, respectively. This monolithic equation system is solved by the projection method using algebraic splitting in the parallel computation environment.

FLIGHT PERFORMANCE

The flight performance of the developed FWNAV has been evaluated using a pair of two distinct computational tools, that is, the nonlinear structural dynamic analysis of the FWNAV and the FSI analysis of the micro wing. Firstly, the former evaluates the flapping amplitude Φ_0 as an output of the nonlinear dynamic behavior of the FWNAV. Then, it is used for the sinusoidal flapping angular displacement $\Phi = \Phi_0 \times \sin 2\pi ft$ as an input for the FSI analysis of the flapping micro wing.

Figure 3: A prototype of the proposed FWNAV.

Table 1: Properties of polyimide materials.

Materials	**Young's modulus**	**Mass density**	**Poisson ratio**
Leading edge	2.5 GPs	1420 kg/m^3	0.289
Wing membrane	3.5 GPs	1420 kg/m^3	0.30

Nonlinear Structural Dynamic Analysis of FWNAV

The problem setup for the nonlinear structural dynamic analysis of the FWNAV along with the material distribution is shown in Fig. 4. The material properties of two polyimides are given in Table 1. In the problem setup, the piezoelectric actuator's output is considered as the forced displacement $u_x = U_x \times \sin 2\pi ft$, and it is applied to an area of the transmission, where the free end of the bimorph is attached. The evaluation of the amplitude of the forced displacement U_x = 81μm has been given in our previous study [11]. In order to avoid sticking between elastic hinges during the flapping motion, the flapping frequency f = 50 Hz is selected [13]. In the problem setup, the lower part of the supporting frame is fixed, where the fixed end of the bimorph actuator is attached. The finite element mesh with 19,582 elements and 98,451 nodes is employed. During the dynamic analysis, the time increment $\Delta t = T/4000$ is used, where $T = 1/f$ is the flapping period.

Figure 5 shows the time history of the flapping angular displacement and the stroke angle from this time history is 43.80°, which will be used as an input for FSI analysis.

FSI Analysis of FWNAV

FSI analysis has been carried out using the in-house code, which was already validated [15]. The problem setup for the FSI analysis is shown in Fig. 6. In this setup, the sinusoidal flapping displacement $\Phi = \Phi_0 \times \sin 2\pi ft$ was applied to the wing base, where $\Phi_0 = 43.80°$ and $f = 50$ Hz were given from the nonlinear structural dynamic analysis of FWNAV. In this setup, the stroke axis coincides with the wing attachment tip line LL' as shown in Fig. 4. The time increment is $\Delta t = T/5000$.

The mesh for the fluid domain is shown in Fig. 7, and the section is shown in Fig. 8, where the mesh for the structural domain as well as the fluid domain is shown. The stabilized linear equal-order-interpolation velocity-pressure elements are used for the fluid mesh with the numbers of nodes and elements are 50,460 and 271,922, respectively, while the MITC shell elements are used for the micro wing with the numbers of nodes and elements are 143 and 120, respectively. In the analysis, the material properties of the fluid (air) are taken as follows; the mass density $\rho_a = 1.205$ kg/m^3 and the viscosity $\mu_a = 1.837\times10^{-5}$ kg/(m sec), while the material properties of the micro wing are shown in the above sections.

The feathering motion is essential for the lift generation during the insect flapping flight. In the FSI model considered here, this motion occurs passively because of the FSI. Figure 9 shows the time history of the feathering motion. From this figure, the value of the mean feathering angle is evaluated as $\psi = 7.47°$. Figure 9 also shows the time history of the lift force, of which mean value is 0.0025mN, and it is less than the gravity force acting on the total weight of FWNAV $w = 4.58$mN. Hence, we will conduct the optimization of FWNAV such that it can generate the sufficient lift to hover.

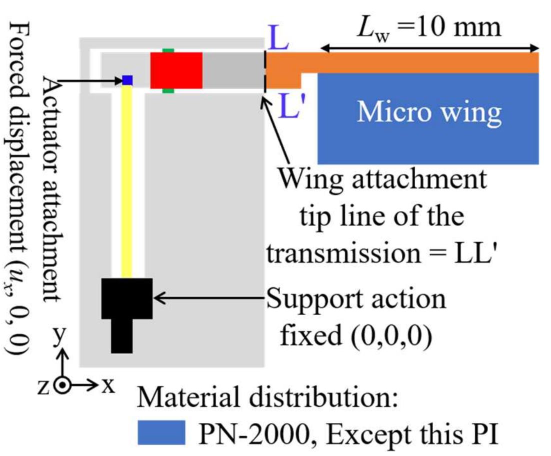

Figure 4: Problem setup for nonlinear structural dynamic analysis of FWNAV.

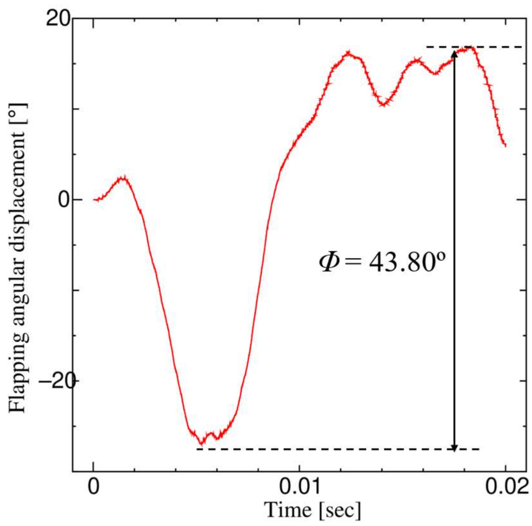

Figure 5: Time history of flapping angular displacement.

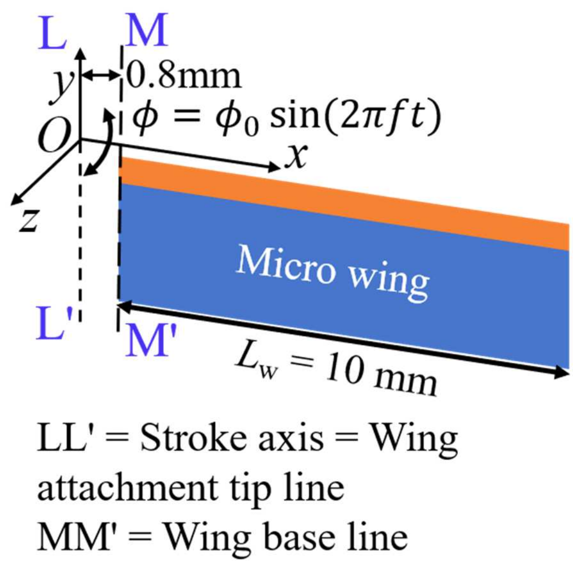

Figure 6: Problem setup for the fluid-structure interaction analysis of FWNAV.

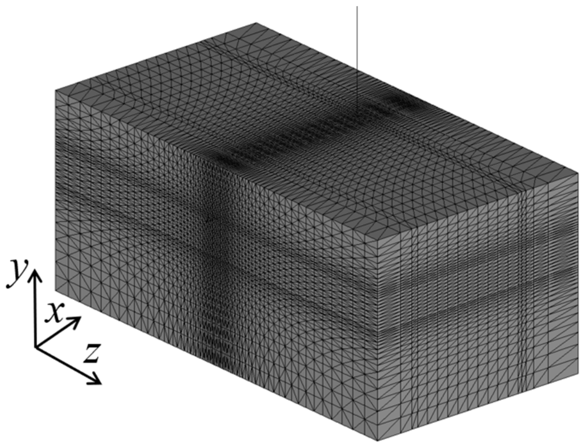

Figure 7: 3-D view of applied fluid mesh during FSI analysis.

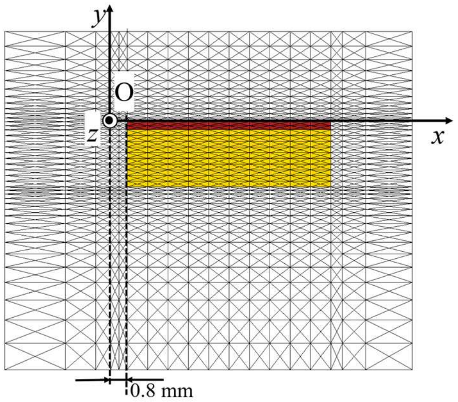

Figure 8: Applied fluid and wing mesh during FSI analysis.

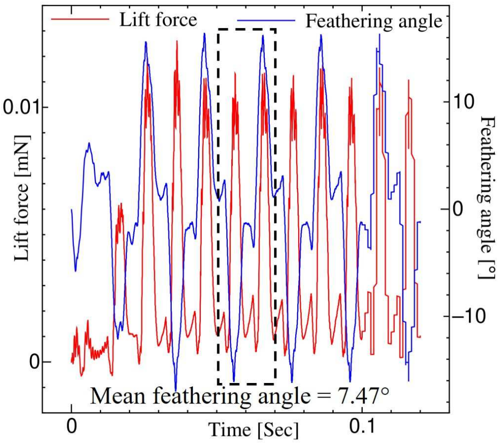

Figure 9: Flight simulation and performance of first prototype polymer micromachined FWNAV

CONCLUSIONS

In this study, we presented a prototype of the polymer micromachined developed FWNAV. Along with this, we have demonstrated the flight simulation and performance evaluation of the developed FWNAV using the nonlinear structural dynamic analysis of FWNAV and the FSI analysis of the micro wing. The flight performance of the prototype has shown the small mean feathering angle and the low mean lift force because of the small stroke angle and the low flapping frequency. Although the mean lift force is less than the weight, it can be increased by optimizing and miniaturizing FWNAV to develop a flyable one. So, this research will edge toward the development of tethered and flyable FWNAVs with the size of the smallest flying natural insects.

ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI Grant Number 20H04199. We appreciate the support from Toray Industries, Inc.

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