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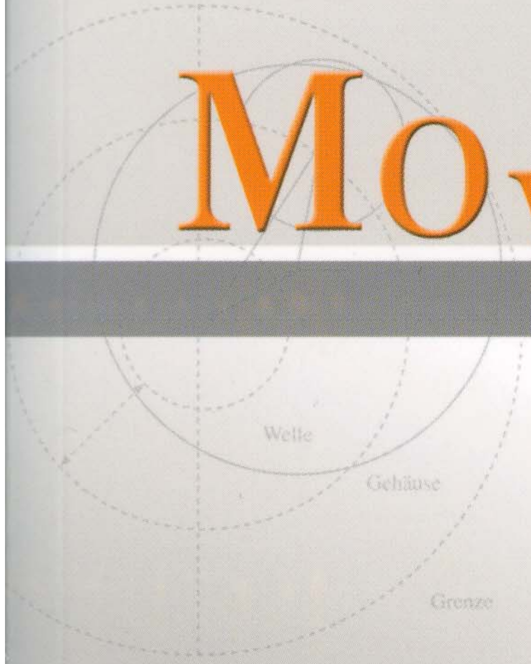

September 15 - 18, 2008
Technische Universitaet Muenchen
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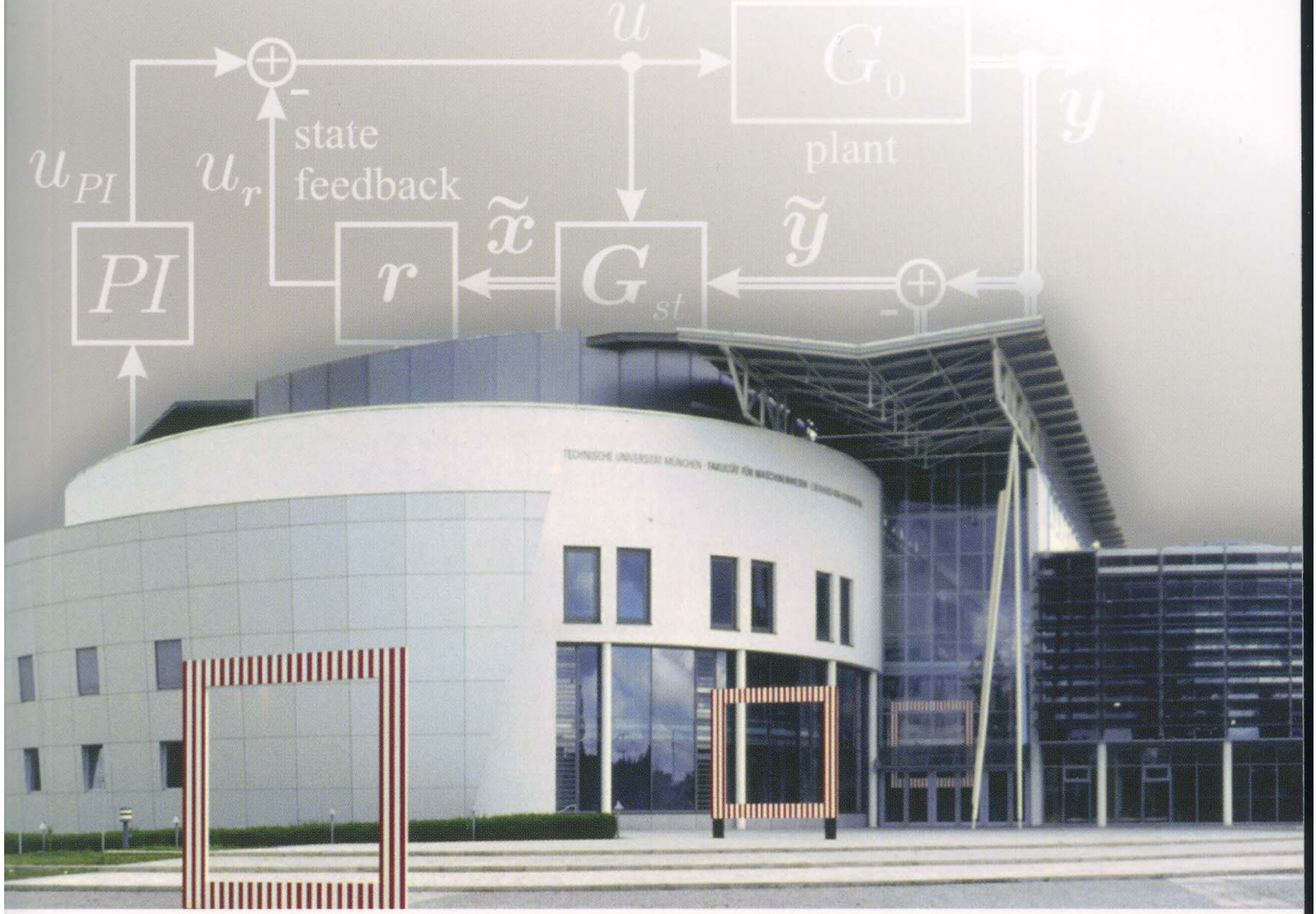

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The 9th International Conference on Motion and Vibration Control

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Optimal Design of a Flexible Flapping Wing Considering Fluid-Structure Interaction

Han, Jae-Hung

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Biological flyers such as birds, bats and insects have spanwise-chordwise anisotropic flexible wings. The deformation of these flapping wings is strongly coupled with aerodynamic forces generated by the wing motion. In order to consider this complicated fluid-structure interaction, aerodynamic and structural analysis technologies should be applied simultaneously. However, it is still extremely difficult to accurately analyze the fluid-structure interaction of the biological or artificial flexible flapping wings. Therefore, for the realization of optimal flapping-wing design and real-time control of artificial flapping-wing vehicles inspired from the biological flyers, an applicable aerodynamic model of flapping wings is indispensable, and an efficient aeroelastic analysis method should be developed.

In the present study, an efficient aeroelastic analysis method for flapping wing flight is proposed, and an optimal design of a flexible flapping wing is performed considering wing flexibility. The aeroelastic analysis method based on the modified strip theory and flexible multibody dynamics is suggested in order to consider higher resultant angle of attack, dynamic stall phenomena and fluid-structure interaction of a flexible flapping wing. The analysis method is also verified with experimental data measured from wind tunnel tests of a rectangular flapping wing, which is made of composite frames and a flexible PVC film skin. The aeroelastic analysis method is applied to optimal design of the rectangular flexible flapping wing. The optimal wing design is performed by considering the variation of wing flexibility in chordwise and spanwise direction. Finally, an optimized wing model can be obtained through the optimal design and the analysis result shows the aerodynamic performance improvement in mean lift and thrust forces up to 24.31% and 32.39%, respectively. We expect that the aeroelastic analysis method proposed in this study can be efficiently applied to optimal flapping-wing design and flapping-wing flight control.

Optimal Design of a Flexible Flapping Wing Using Fluid-Structure Interaction Analysis

Dae-Kwan Kim and Jae-Hung Han

Abstract An aeroelastic analysis method for flapping-wing flight is proposed by coupling an unsteady aerodynamic model and a structural dynamic model of a flexible flapping wing. For the efficient analysis of fluid-structure interaction problems, the aerodynamic and structural models are improved by using the modified strip theory and the flexible multibody dynamics, respectively. The aeroelatic method is verified with experimental data measured from wind tunnel tests of a rectangular flapping wing. Using the proposed aeroelastic analysis method, an optimal design of a rectangular flapping wing is performed by considering the variation of wing flexibility in chordwise and spanwise direction. The analysis result shows that the aerodynamic performance of the flexible flapping wing can be effectively improved through the optimal design for the chordwise and spanwise wing flexibility.

1 Introduction

Biological flyers such as birds, bats and insects have spanwise-chordwise anisotropic flexible wings. Deformation of these flapping wings is strongly coupled with aerodynamic forces generated by the wing motion [1-2]. In order to consider this complicated fluid-structure interaction, aerodynamic and structural analysis technologies must be simultaneously applied. However, it needs very expensive computational cost and is still extremely difficult to analyze accurately the fluid-structure interaction of the biological or artificial flexible flapping wings. Therefore, for the realization of optimal flapping-wing design and stable control of artificial flapping-wing vehicles inspired from the biological flyers, an efficient aerodynamic model of flapping wings is indispensable, and an efficient aeroelastic analysis method should be developed.

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There have been many studies on aerodynamics and mechanism of flapping-wing flight [3-7]. For simplicity, however, the rigid wings have been considered for most previous studies. Actually, the biological flyers utilize the local elastic deformation of their wings generated by the wing inertial force and the aerodynamic force. The local deformation produces the sectional pitching motion, so that the appropriate effective angle of attack is generated continuously with the wing span. In case of the artificial flapping flyers, such as in ornithopters, the local deformation is determined by the structural stiffness of frames in chordwise and spanwise directions. Therefore, in order to design a high-performance flapping-wing vehicle, the structural flexibilities in both the directions should be optimized through the aeroelastic analysis research.

In the present study, an efficient aeroelastic method is suggested by using the unsteady aerodynamic model and the structural dynamic model of a rectangular flapping wing. The aeroelastic model of the rectangular flapping wing was verified with the experimental data. Finally, an optimal design of the present flapping wing was performed according to the various wing flexibilities.

2. Rectangular Flapping Wing

The rectangular flapping wing has been manufactured in order to investigate the aeroelatic characteristics of a flexible flapping wing. As shown in Figure 1, the wing consists of graphite/epoxy composite frames and a flexible film skin. The wing has a rectangular wing shape with the aspect ratio of 5.58 and the half span of 54cm. The root of the leading edge spar is driven by a transmission system, which converts the rotary motion of the driving DC motor into the flapping motion [8]. The rear spar is connected to the body by a hinge joint in order to generate the passive pitching motion induced by the wing flexibility. To measure the horizontal and vertical constraint forces simultaneously, the driving mechanism is mounted on a test stand consisting of two load cells in each direction.

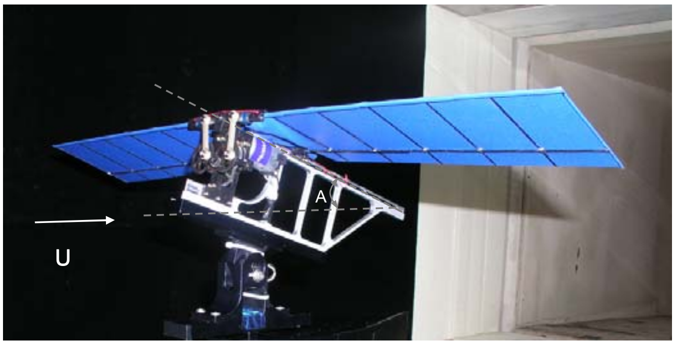

Figure 1. Rectangular flapping wing embedded on the test stand.

In this study, a structural dynamic model of the rectangular flexible flapping wing is established by using the flexible multibody dynamics and to consider both the rigid wing motion and the local elastic deformation [9]. The equation of motion of the flapping wing can be derived from Lagrange's equation. Moreover, for an efficient analysis of the fluid-structure interaction problem, the reduced dynamic model is obtained by using a modal approach as follows:

$$\begin{bmatrix} m_{rr}^{\alpha} & m_{r\theta}^{\alpha} & m_{re}^{\alpha} \\ & m_{\theta\theta}^{\alpha} & m_{\theta e}^{\alpha} \\ Symmetric & & m_{ee}^{\alpha} \end{bmatrix} \begin{Bmatrix} \ddot{\hat{r}}_0^{\alpha} \\ \ddot{\theta}^{\alpha} \\ \ddot{\xi}_e^{\alpha} \end{Bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \bar{k}_{ee}^{\alpha} \end{bmatrix} \begin{Bmatrix} \hat{r}_0^{\alpha} \\ \theta^{\alpha} \\ \xi_e^{\alpha} \end{Bmatrix} = \begin{Bmatrix} \hat{Q}_0^{\alpha} \\ \hat{Q}_{\theta}^{\alpha} \\ \hat{Q}_e^{\alpha} \end{Bmatrix} \tag{1}$$

where $\hat{r}_0$ and θ are the translation and the rotational vectors of $\hat{R}_0$, and ξ_e is the generalized coordinate vector of the elastic deformation u_e . The right side of the equation of motion, $\hat{Q}$, is the generalized external force vector. In this equation, the elements of the mass and the stiffness matrixes are the time-dependent properties determined according to the wing motion, so that Eq. (1) is the nonlinear equation of motion for the flexible flapping wing.

3. Aeroelastic Analysis

To analyze the aeroelastic problem of the rectangular flapping wing, the structural model and the aerodynamic model should be interactively solved. In the present work, the unsteady aerodynamic forces and moment applied on the wing surface is calculated by using the modified strip theory improved by the present authors [10]. The dedicated coupling method between the aerodynamic and structural models is suggested, and then the aeroelastic analysis result of the rectangular flapping wing is compared with experimental data obtained from a low-speed wind tunnel test.

3.1 Fluid-structure interaction

The fluid-structure interaction of the flapping wing is analyzed by coupling the aerodynamic and the structural models. At a time step t_i , the motion and deformation data of the wing calculated by the structural module are used as the input values of the aerodynamic model to obtain the aerodynamic force and moment of the wing, and then the structural dynamic responses are also calculated by using the obtained aerodynamic outputs. This iterative calculation is successively performed until the structural response satisfies a convergence criterion in which the difference of the total elastic deformation is restricted to a sufficiently small value. In this analysis, it is assumed that the pitch angle (θ_x) is the same as the flapping axis angle (A) shown in Figure 1, and the flapping angle (θ_z) driven by the driving motor is a sinusoidal passive motion as follows:

$$\theta_z(t) = \theta_0 + \theta_1 \sin(2\pi f_z \cdot t) \tag{2}$$

where, f_z is the flapping frequency, θ_0 is the mean flapping angle and θ_1 is the amplitude of the sinusoidal flapping angle. In the dynamic analysis, as shown in Figure 2, the steady, transient and unsteady phases of the enforced wing motion are successively calculated by using Lagrange multiplier technique. The time integration of the coupling problem is conducted by using Newmark beta method. The final calculation time is decided by the period of the steady mean pitch angle $\bar{\theta}$.

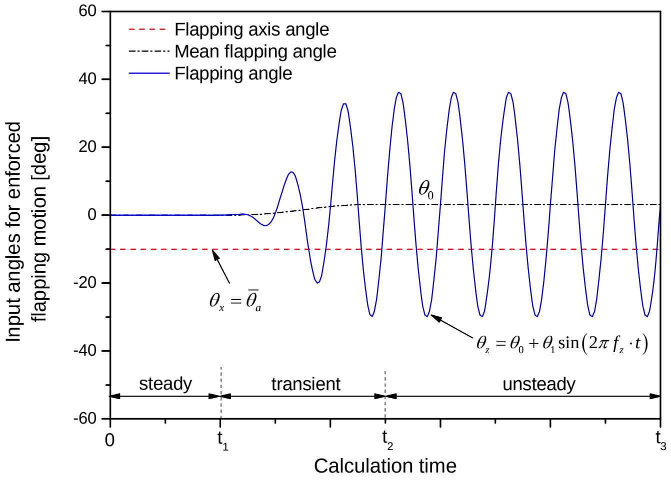

Figure 2. Input angles for enforced flapping motion.

3.2 Aeroelastic analysis results

Using the fluid-structure coupling method, the aeroelastic analysis of the flapping wing is performed. The analysis results are compared with the experimental data measured from the aerodynamic test in a low-speed wind tunnel with $A = 20\,\text{degrees}$, $f_z = 4\,Hz$ and the free stream velocity of $6\,m/s$. Figure 3 shows the comparison of the vertical and horizontal constraint forces between the measured and the analyzed data. This result clearly demonstrates that the maximum force in the vertical direction is generated at the middle of the down-stroke where the resultant velocity V was maximized. Moreover, the distortion in the constraint force signals can be found, and this is probably because of the unsymmetrical elastic deformation of the wing between up- and down-strokes. From this result, it is evident that the aeroelastic analysis performed by using the reduced dynamic model compares well with the experimental results

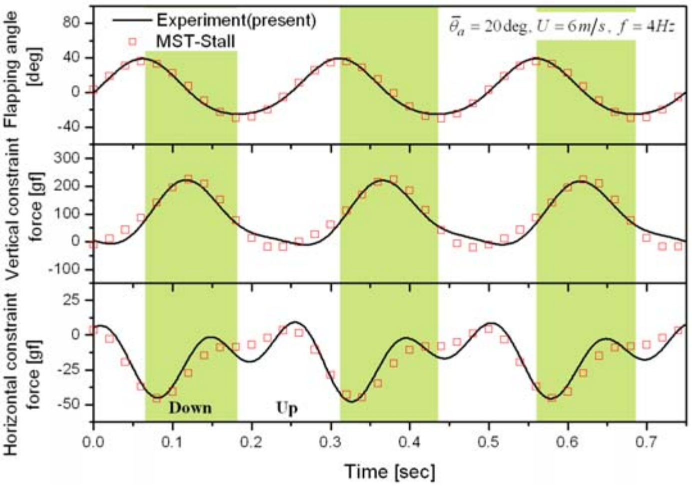

Figure 3. Comparisons of constraint forces between experiment and analysis.

4 Optimal Design of Wing Flexibility

The aerodynamic performance of the flapping wing according to various wing flexibilities is investigated by using the fluid-structure interaction analysis method. This is also an optimal design problem of determining the wing flexibility to achieve the higher aerodynamic performance than that of the present wing.

The rectangular flapping wing consists of one leading edge spar, six ribs and one rear spar, as shown in Figure 1. The leading and rear spars have nonuniform frames like shown in Figure 4 to increase the spanwise wing flexibility. One of the methods for modification of the wing flexibility is to change the sectional area of the frames. In the present work, the section factor (SF) is equally applied to the frames for variation of the sectional area. It is assumed that the chordwise flexibility is determined by the stiffness of ribs and the spanwise flexibility is determined by that of the leading edge and rear spars.

The aeroelastic analysis is performed with the variation of the section factor from 0.7 to 2.0 for the spanwise flexibility and from 0.8 to 3.0 for chordwise flexibility. The analysis conditions are $A = 15°$, $U = 8\,m/s$ and $f_z = 8Hz$. Figure 5 shows the mean lift and thrust coefficients according to the spanwise and chordwise section factors. From the result, the variation of the mean lift coefficient is found to be larger than that of the trust coefficient, and that the lift and thrust coefficients mostly depend on the spanwise wing flexibility except for the low section factor region less than about 1.0.

The aerodynamic performances of five flexibility cases including the present model are listed in Table 1. The highest aerodynamic performance is generated in Case-4, where the lift and thrust coefficients are increased up to 24.31% and 32.39%, respectively. This analysis result clearly demonstrates that the optimal design of flexible flapping wing should be performed through the fluid-structure interaction analysis.

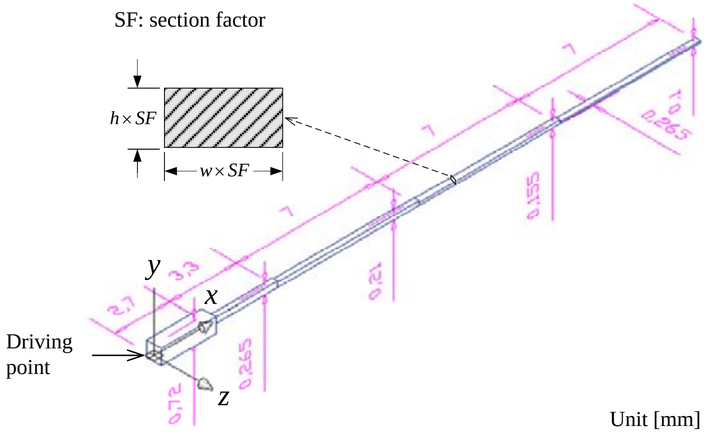

Figure 4. Configuration of the leading edge spar.

Table 1 Comparisons of 1st modes and aerodynamic coefficients.

Case #	Spanwise section factor	Chordwise section factor	Mean lift coefficient	Mean thrust coefficient
Present	1.0	1.0	0.576	-0.096
1	0.7	0.8	0.378	-0.286
2	0.7	3.0	0.599	-0.074
3	2.0	1.8	0.541	-0.104
4	1.3	1.8	0.716 (+ 24.31 %)	-0.065 (+ 32.29 %)

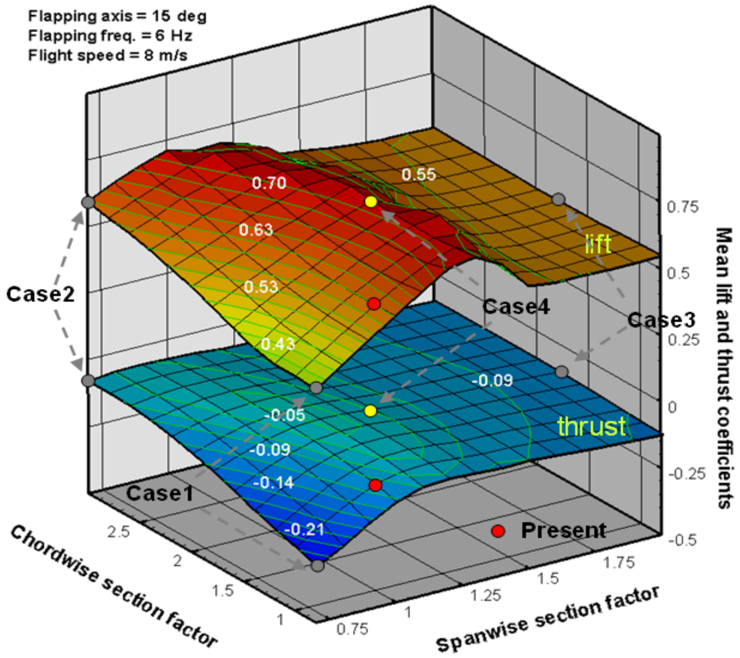

Figure 5. Aerodynamic coefficients according to spanwise and chordwise section factors.

5. Conclusions

In the present study, an efficient aeroelastic analysis method for flapping wing flight was proposed, and an optimal design of a flexible flapping wing was performed by considering the wing flexibility. The aeroelastic analysis method based on the modified strip theory and flexible multibody dynamics was suggested in order to consider the fluid-structure interaction phenomena of a flexible flapping wing. The analysis method was also verified with experimental data measured from wind tunnel tests of a rectangular flapping wing. The aeroelastic analysis method was applied to optimal design of the flapping wing with the consideration of the various wing flexibilities in chordwise and spanwise direction. Finally, an optimized wing model can be obtained and the analysis result shows the aerodynamic performance improvement especially in mean lift and thrust forces up to 24.31% and 32.39%, respectively. We expect that the aeroelastic analysis method proposed in this study can be effectively applied to optimal flapping-wing design and flapping-wing flight control.

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