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AERODYNAMIC RESEARCH OF FLEXIBLE FLAPPING WING BY COMBINING DIC AND CFD APPROACHES

Yang Wenqing, Song Bifeng, Song Wenping, Wang Liguang, Fu Peng, Xu Jianhua
School of Aeronautics, Northwestern Polytechnical University, Xi'an, China. 710072

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Abstract

The aerodynamic performance of flexible flapping wing is researched by combining Digital Image Correlation (DIC) and CFD approaches in this paper. The aerodynamic characteristics is complex for flapping wing micro air vehicles because they always use flexible wings, which will deform in flapping flight under the effect of aerodynamic and inertial forces. The relations among deformation and forces are mutual influence. In actually, the deformation is difficult to be obtained for its instantaneous characteristics. DIC technique can solve this problem by combine with the high-speed imaging devices. After the deforming process is obtained in a high-precision manner, the flow features can be simulated in a detail way by numerical method accordingly. The numerical results can be validated by compare with the experimental data. This method has highly temporal and spatial resolutions; the temporal resolution is obtained by DIC technique and the spatial resolution by CFD simulation. And it can be used to measure and analyze directly the characteristic parameters of flexible flapping wing, such as the relation and influence mechanism between deformation and aerodynamic forces.

1 Introduction

Micro flexible flapping wing has attracted much interest because of its excellent aerodynamic properties. However, its fluid-structure coupling mechanism is an unveiled problem, which restricts its potential applications. There are many methods in investigating the fluid-structure coupling mechanism of flexible flapping wing. Researchers have founded many theories. Here, we catalogued these studies into four kinds.

a) Preset meaningful structure deformation [1-9]. Such researches focus on the aerodynamic phenomenal caused by structure deformation. The deformation manners are inspired by natural flyers, and are assumed in a proper way. These studies help people understand basic characteristics of flexible flapping wings but not tell the truly coupling relation between structure and aerodynamic performance. The conclusions of these papers even conflict with each other for their deforming manners are different. Some [3-4] showed small range of chord deformation is beneficial for increasing thrust; while some [5-7] showed large range of chord deformation is beneficial for increasing thrust.

b) Simplify structure or aerodynamic model [10-15]. Isogai and Harino [10] presented a method for the optimum aeroelastic design of a flapping wing employing a lifting-surface theory as an aerodynamic tool and the complex method as the optimization algorithm. Lee et al. [11-12] investigated the effect of flexibility on the generation of propulsion of 2D flapping wing. The lattice Boltzmann method with an immersed boundary technique is used to simulate the fluid, while the finite element method with Euler beam elements is used to model structural deformation of the flexible plate. Jaworski and Gordnier [13] investigated the aerodynamics and aeroelastic response of a membrane wing under prescribed motion using a high-order, two-dimensional Navier-Stokes solver coupled to a geometrically nonlinear membrane model.

Fluid-structure coupling research involves the interdisciplinary. The iteration between two disciplinarians is always ten or more times. Thus, appropriate simplifications are always taken into analysis both in fluid or structure simulation to testify the basic interaction phenomenon.

c) Full coupling research. There are also some full coupling researches, where the flow fields are simulated by solving Navier-Stokes equations and the structure dynamics are fully modeled and solved. Unger et al. [16] also considered the transition. This kind of research can show the entire coupling process but have much difficulty in 3D simulation.

d) Experimental based research [17-19]. The most advantage of experimental tests is it can obtain the real situation directly. For now, the continuous improvement of experimental means will help a lot for researchers to find new scientific phenomena and mechanisms of flexible flapping wing.

From above analysis, although the emergence of a large number of studies helps researchers understand a lot, the precise structure deformation is still hard to tested or simulated in detail analysis. Published papers still have no uniform conclusions, even conflict from each other.

In this paper, we are going to investigate the precise correspondence between passive flexible structural deformation and aerodynamic forces of micro flapping wings. To take the real situation as basic, the experimental test is chosen to obtain the flexible deformation process directly. Based on precise experiments, the CFD method will be used to simulate the flapping wing to analyze the unsteady flow in detail.

2 Experimental Setup

Wing deformation can be measured by many efforts, including projection moiré interferometry (PMI) [20-22], photogrammetry [23-24], and finite element methods [25]. PMI provided useful out-of-plane displacements; it does not yield in-plane strains. Photogrammetric techniques only produced low spatial-resolution data sets and would require interpolation techniques to determine displacements for higher density grids. It is necessary to get high spatial resolution data, as well as material properties, to accurately model the fluid-structure interactions of a deformable flexible wing of vehicles. [26-28]

The detailed description of deformation process can be obtained by high-speed imaging technique combined with Digital Image Correlation (DIC). The unsteady aerodynamic forces are synchronously obtained by high-precision six-component dynamic strain balance. Fig. 1 shows the experimental setup of high-speed imaging device and wind tunnel experiments system.

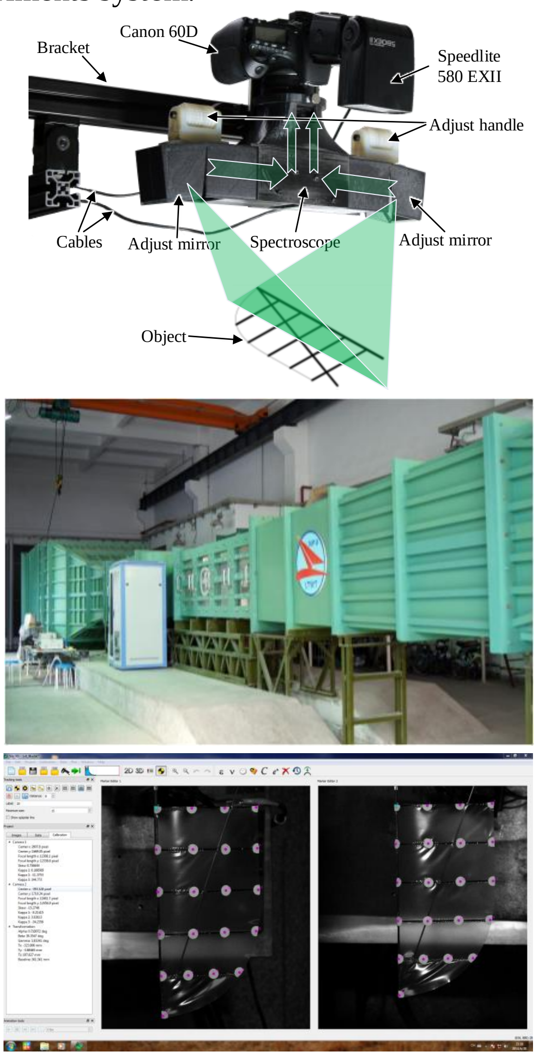


Fig. 1. (a) High-Speed Imaging Device Employed With DIC Technique; (b) Setup of Wind Tunnel Experiments System; (c) Correlation of the Two Pictures.

All tests were performed at the Low Turbulence Wind Tunnel (LTWT) of

Northwestern Polytechnical University of China. The wind tunnel has a 1.05m×1.2m×2m test section with optical access from the sidewalls and the ceiling. Typical testing Reynolds numbers, based on wing chord geometry and flow speeds, range between 50,000 and 100,000. A six-component (three forces and three moments) balance was used for aerodynamic force (lift, drag, and side) and moment (roll, pitch, and yaw) measurements. The balance is attached to a pitch-adjustable arm which is used to set model angle of attack (AOA). A dedicated multi-channel data acquisition system and in-house software developed in LabVIEW to record the tunnel speed, model inclination and force/moment measurements.

Here, we should notice that the forces tested by balance include aerodynamic and inertial forces. They should be separated in the data processing. The inertial force is determined by the mass times acceleration, and the acceleration is calculated through the second derivative of displacement. There will be some error included in the inertial calculation, but this is still an effective method to obtain the pure aerodynamic force generated by flapping wing.

A DIC system was used to measure the wing displacements and according deformations. In order to capture the three-dimensional features of the flexible flapping wing, a new method by using a single camera for capturing stereo-images is developed. An adjustable single-lens dual optical path spectroscope is produced to obtain stereo-images, as shown in Fig. 1(a). A single picture captured by this system is cut out into two stereo pictures, as shown in Fig. 1(c). Because the two pictures are taken from the same time, so the stereo pictures are exactly synchronous. The camera was installed above the wind tunnel ceiling. The operating principle of the DIC technique is to determine the displacements of a specimen under load by tracking the deformations of specific markers previously applied on its surface. The marker pattern is digitally acquired by the camera during loading. The spatial place of the markers, and hence surface position, are determined by correlation between the two images. The reconstruction of the 3D features of the specimen is then possible. More details see reference [29].

3 Model and Test

The flexible flapping wing skeleton is constructed of carbon fiber composites, which is covered with the polyester membrane as wing skin.

For the DIC techniques, there are two patterns of surface treatment, random speckling of whole surface and specific marker of discrete points respectively. The random speckling can obtain surface displacement in total, but except the outmost circle because of the calculation algorithm. However the leading edge deformation is our main concern, so that the markers by discrete points are chosen to obtain the specific displacement of several important joint points. The completed wing model used for testing in the wind tunnel has been shown in Fig.1(c).

The planform of the wing is combined by a rectangle and an ellipse, with an aspect ratio of 4.5, a 200 mm wing length and a 100 mm root chord. The wing is with camber of the upper profile of airfoil E378. The leading edge spar and the diagonal batten are off-the-shelf carbon rods with diameter of 2 mm and 1.8 mm, respectively. The rib of the wing is formed in a die with unidirectional carbon fiber.

The objective of the experiment was to determine the deformation of the wings under unsteady aerodynamic loads generated by flapping motion, while acquiring simultaneous aerodynamic force data.

The images taken for DIC were of the final deformed wing in a whole flapping cycle. The absolute deformation can be obtained by subtract the rigid body movement, which is determined by the flapping mechanism position.

The procedural steps were:

1) Start the wind tunnel and flap the wings to stable.

2) Take the pictures of the deformed wing in several flapping cycles, and record the loads simultaneously.

3) Stop the wind tunnel and move the model to the next state.

After the test, the images and data were dealt with to get deformed surface cycle for the CFD simulation.

4 Computational method

For the precise deforming process has been confirmed by experiment, the CFD method is an effective way to observe the flow detail. The Navier-Stokes equations are chosen as the low Reynolds number features of micro flapping wing. Tested deforming process is composed by separated points, which is fitted by spline fitting method and discretized again in a proper way for numerical simulation. After that, the flow details over flapping wing are obtained.

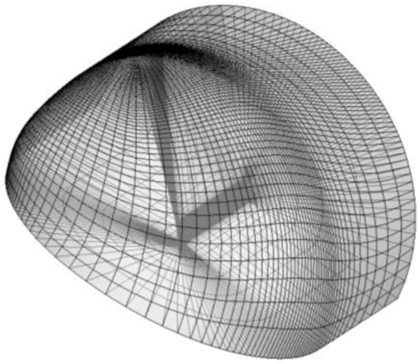
The unsteady aerodynamics of the flapping wing is derived by solving three-dimensional unsteady compressible Navier-Stokes equations, which can be written as,

$$\frac{D}{Dt}\iiint_{\Omega} W dV + \iint_{\partial\Omega} \overline{\overline{H'}} \bullet ndS = \iint_{\partial\Omega} \overline{\overline{H_v}} \bullet ndS \qquad (1)$$

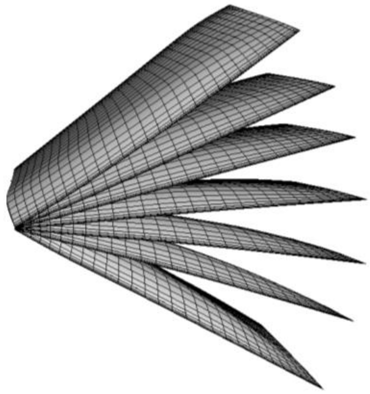
where, Ω is the control volume, S, n denote the boundary of control volume and its unit-normal outer vector, H', H_v denote the inviscous and viscous flux, respectively.

The governing equations are solved by means of a cell-centered finite volume approach using a LU-SGS time-stepping method with multi-grid acceleration, and the SST turbulence model is applied.

Because there is a wide range of bending/twisting movements existed during flexible flapping wing flight, it is necessary to develop an automatic mesh generation program, which is able to accommodate a large range of wing movement. In this paper, a moving grid methodology based on infinite interpolation is used for automatic mesh generation of flexible flapping wing. A structural CO type grid of flapping wing is used for aerodynamic simulations. Grid size is 176, 56, and 60 in the tangential, radial and spanwise directions respectively. Fig.2 shows the grid system of the flapping wing generated by grid generation program.



(a)

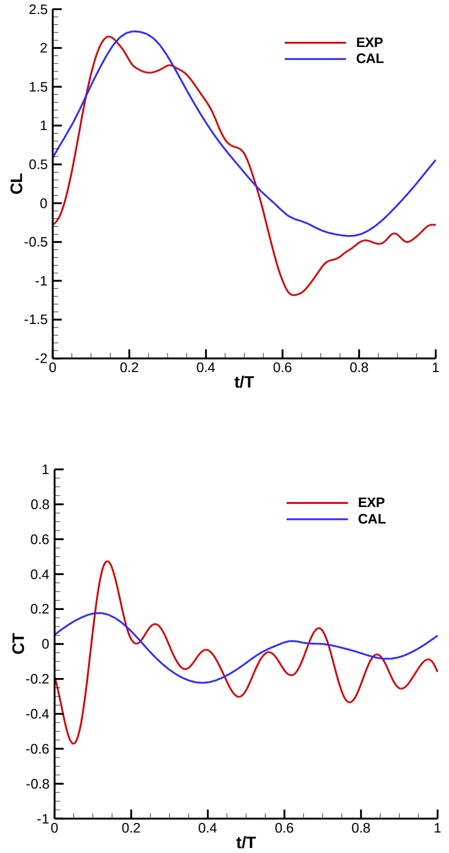


(b)

Fig.2. (a) The Topology of the Grid Distribution of the Wing in the Fluid Computation; (b) The View of Wing Surface Grid.

5 Results and discussions

We have carried out experiments and numerical simulations to testify the feasibility of the proposed research plan. The results show that the deformation process can be captured during the entire flapping cycle. Then, the detail flow fields are simulated by CFD. Fig. 3 shows the aerodynamic forces coefficients comparisons of experimental and calculating results. The states parameters are chosen in the range of bird like scale. The AOA is 0°, the flapping frequency is 6Hz, the flapping amplitude is ±33.3° and the free stream velocity is 6m/s.



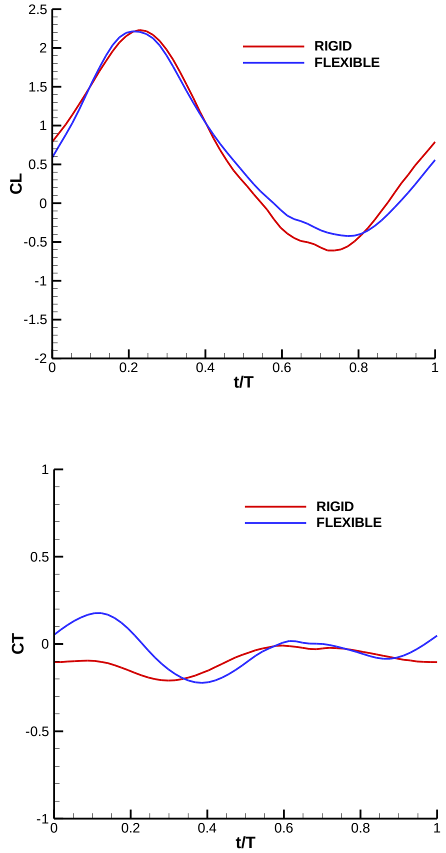
(a)

(b)

Fig.3. Aerodynamic Forces Coefficients Comparisons of Experimental and Calculating Results.

During the wind tunnel test, a wing vibration phenomenon is observed when the wing flap close to top and bottom position. This vibration might be caused by the coupling between driving frequency of mechanism and nature frequency of wing structure. Here, we didn't concentrate it, and we may discuss this phenomenon deeply in later research. For CFD simulation, this vibration is smoothed to get convergent results. That might be the cause of results deviations of calculation from experiments. In totally, the results comparisons between wind tunnel test and CFD simulation are close to each other, which proved the effectiveness of the mixed research method.

The aerodynamics of rigid wing is also calculated, which is compared with the flexible flapping wings, shown in Fig.4.



(a)

(b)

Fig.4. Results Comparison Between Rigid and Flexible Flapping Wing.

The results show that the flexible wings have better aerodynamic performance than the rigid wing, especially for the thrust. An important effect is the flexible deformation manner will induce a torsion effect in chord wise when the leading edge is more rigid, which will induce much significantly greater thrust force, that is a very favorable phenomenon for the flapping flight.

The surface pressure contours are shown in Fig.5. There is obvious deformation observed. It can be seen that the flexible wings have larger flapping amplitude than the rigid wing for the flexible deformation, which will induce the larger amplitude of lift fluctuation curve in a cycle.

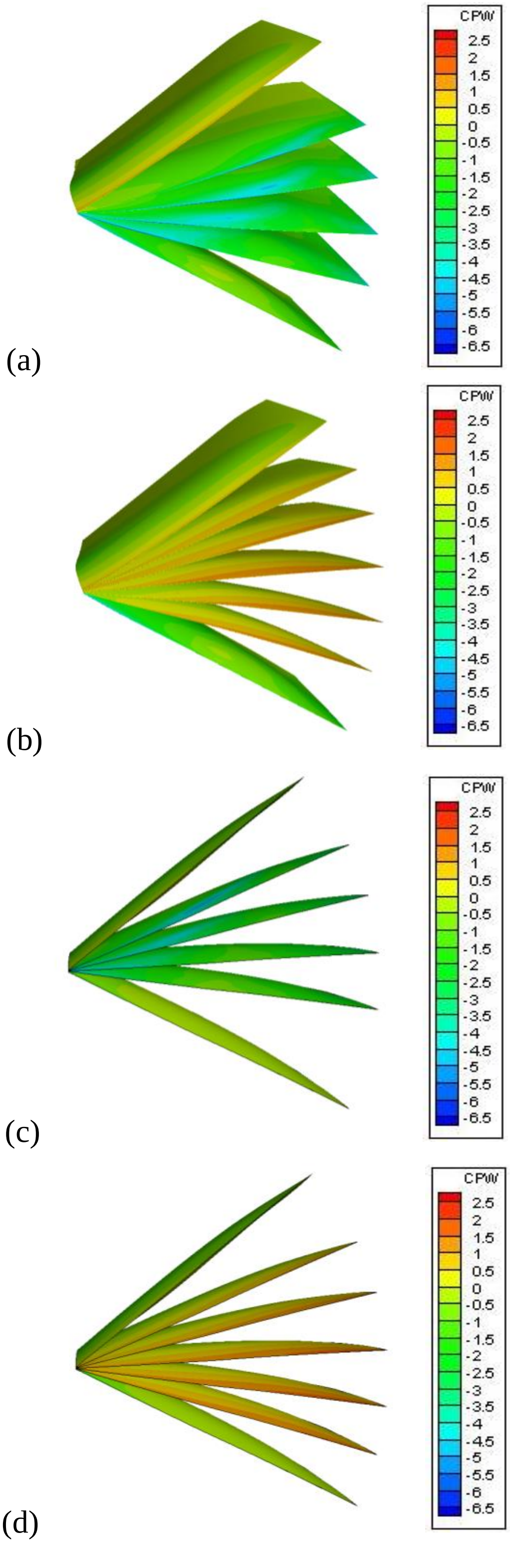


Fig.5. Pressure Contour of Flexible and Rigid Flapping Wing: (a) Down Stroke of Flexible Wing; (b) Up Stroke of Flexible Wing; (c) Down Stroke of Rigid Wing; (d) Up Stroke of Rigid Wing.

6 Conclusions

DIC represents a reliable method to obtain the global deformations and rigid body translations of a model during generic tests in wind tunnels, providing high-spatial resolution 3D displacements. An experimental setup was conceived and assembled around a low-speed wind tunnel, integrating DIC and aerodynamic coefficient measurements.

After the deformation process is obtained by DIC technique, the CFD method is implemented to research the flow detail. The numerical simulation results have good accordance with the wind tunnel test results, which prove the correctness of low Reynolds flow simulation. The fluid details were obtained by the CFD method to assistant the understanding of flexible effects. The comparison between rigid and flexible flapping wings is obtained by CFD method. The results prove the flexible deformation can improve the aerodynamic performance obviously.

This study aims at developing a method combining experiment and numerical simulation, which has highly temporal and spatial resolutions, the temporal resolution is obtained by DIC technique and the spatial resolution by CFD simulation, and can be used to measure and analyze directly the characteristic parameters of flexible flapping wing, such as the deformation and aerodynamic forces. This paper has significance to understand and advance the mechanism of micro flexible flapping wing.

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References

[1] Gerdes J W, Gupta S K. A Review of Bird-Inspired Flapping Wing Miniature Air Vehicle Designs [J]. *Journal of Mechanisms and Robotics*. 2012, 4: 1-11.

[2] Shyy W, Aono H, Chimakurthi S K, et al. Recent progress in flapping wing aerodynamics and aeroelasticity[J]. *Progress in Aerospace Sciences*.

2010, 46: 284-327.
[3] Miao J M, Ho M H. Effect of flexure on aerodynamic propulsive efficiency of flapping flexible airfoil [J]. *Journal of Fluids and Structures*. 2006, 22: 401-419.
[4] Tay W B, Lim K B. Numerical analysis of active chordwise flexibility on the performance of non-symmetrical flapping airfoils [J]. J*ournal of Fluids and Structures*. 2010, 26: 74-91.
[5] Yang W, Song B, Song W, et al. The effects of span-wise and chord-wise flexibility on the aerodynamic performance of micro flapping-wing [J]. *Chinese Science Bulletin*. 2012, 55(22): 2887-2897.
[6] Tian F, Luo H, Song J, et al. Force production and a symmetric deformation of a flexible flapping wing in forward flight [J]. *Journal of Fluids and Structures*. 2013, 36: 149-161.
[7] Le T Q, Ko J H, Byun D, et al. Effect of Chord Flexure on Aerodynamic Performance of a Flapping Wing[J]. *Journal of Bionic Engineering*. 2010, 7: 87-94.
[8] Ghommem M, Hajj M R, Mook D, et al. Global optimization of actively morphing flapping wings [J]. *Journal of Fluids and Structures*. 2012, 32: 210-228.
[9] Du G, Sun M. Aerodynamic effects of corrugation and deformation in flapping wings of hovering hoverflies [J]. *Journal of Theoretical Biology*. 2012, 30: 19-28.
[10] Isogai K, Harino Y. Optimum Aeroelastic Design of a Flapping Wing [J]. *Journal of Aircraft*. 2007, 44(6): 2040-2048.
[11] Lee J, Shin J, Lee S. Fluid–structure interaction of a flapping flexible plate in quiescent fluid [J]. *Computers & Fluids*. 2012, 57: 124-137.
[12] Lee J, Lee S. Fluid–structure interaction for the propulsive velocity of a flapping flexible plate at low [J]. *Computers & Fluids*. 2013, 71: 348-374.
[13] Jaworski J W, Gordnier R E. High-order simulations of low Reynolds number membrane airfoils under prescribed motion [J]. *Journal of Fluids and Structures*. 2012, 31: 49-66.
[14] Yang W, Song B, Song W, et al. Fluid-Structure Coupling Research for Micro Flapping-Wing: *27th International Congress of the Aeronautical Sciences*[C]. Nice, France: 2010.
[15] Pourtakdoust S H, Aliabadi S K. Evaluation of flapping wing propulsion based on a new experimentally validated aeroelastic model [J]. *Scientia Iranica*. 2012, 19(3): 472-482.
[16] Unger R, Haupt M C, Horst P, et al. Fluid–structure analysis of a flexible flapping airfoil at lowReynolds number flow [J]. *Journal of Fluids and Structures*. 2012, 28: 72-88.
[17] Lin C, Hwu C, Young W. The thrust and lift of an ornithopter's membrane wings with simple flapping motion [J]. *Aerospace Science and Technology*. 2006, 10: 111-119.
[18] Mazaheri K, Ebrahimi A. Experimental investigation of the effect of chordwise flexibility on the aerodynamics of flapping wings in hovering flight [J]. *Journal of Fluids and Structures*. 2010, 26: 544-558.
[19] Hu H, Kumar A G, Abate G, et al. An experimental investigation on the aerodynamic performances of flexible membrane wings in flapping flight [J]. *Aerospace Science and Technology*. 2010, 14: 575-586.
[20] Fleming G A, Burner A W. Deformation measurements of smart aerodynamic surfaces, SPIE Paper No. 3783-25, 4*4th Annual SPIE International Symposium on Optical Science, Engineering, and Instrumentation—Optical Diagnostics for Fluids/Heat/Combustion and Photomechanics for Solids*, July.1999.
[21] Fleming G A, Bartram S M, Waszak M R, Jenkins L N. Projection Moire interferometry measurements of micro air vehicle wings, *SPIE Paper no. 4448-16*, November.2001.
[22] Burner A W, Flemming G A, Hoppe J C. Comparison of three optical methods for measuring model deformation, *AIAA Paper 2000-0835*, January.2000.
[23] Waszak M R, Jenkins L N, Ifju P G. Stability and control properties of an aeroelastic fixed wing micro aerial vehicle, *AIAA Paper 2001–4005*, August.2001.
[24] Spain C V, Heeg J, Ivanco T G, Barrows D A, Florance J R, Burner A W. Assessing videogrammetry for static aeroelastic Testing of a Wind-Tunnel Model, *AIAA Paper 2004-1677*, April.2004.
[25] Hooker J R, Burner A W, Valla R. Static aeroelastic analysis of transonic wind tunnel models using FE methods, *AIAA Paper 97-2243*, June.1997.
[26] Nassefa H S, Pornsinsirirakb H N, Taib Y C, Ho C M. Unsteady aerodynamics and flow control for flapping wing flyers. *Prog Aerosp Sci*. 2003.39:635–681.
[27] Pennycuick C J, Lock A. Elastic energy storage in primary feather shafts. *J Exp Biol*.1976. 64:667–689.
[28] Combes S A, Daniel T L. Flexural stiffness in insect wings II. Spatial distribution and dynamic wing bending. *J Exp Biol*. 2003.206:2989–2997.
[29] Wang L, Song B, Yang W. Experimental Characterization of a Flexible Membrane Flapping-Wing in Forward Flight. ICAS2014--*29th Congress of the International Council of the Aeronautical Sciences*. St. Petersburg, Russia; Sep. 7-12, 2014.

Contact Author Email Address

Mailto: yangwenqing@nwpu.edu.cn