A Novel Micro Air Vehicle with Flexible Wing Integrated with On-board Electronic Devices

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Abstract*—This paper presents an electrically powered Micro Air Vehicle (MAV) with a flexible wing integrated with on-board electronic components that is built at Tsinghua University. The low aspect ratio wing, adopting the airfoil of S5010 and Zimmerman shape, is made up of a flexible printed circuit membrane (FPCM) that covers a thin carbon fiber skeleton. The real MAV prototype is tested in a low-speed wind tunnel in order to evaluate its aerodynamic characteristics. The comparing experiments are conducted on the flexible wing and its rigid counterpart with the same size and the same wing shape to illustrate the aerodynamic advantages of the flexible wing. The results of the wind tunnel experiments indicate that the flexible wing has a larger angle of stall, bigger maximum lift coefficient than the rigid one. However, the lift-drag ratio of the flexible wing varies in a complex way because the flexible wing also increases the drag with the lift growth. The FPCM functions as both the skin of the aircraft wing and the supporting substrate for the electronic components, such as micro hot-film flow speed sensors that are used to determine 3 fundamental flight parameters: air speed, angle of attack and sideslip angle. In addition, most of the signal processing circuits is distributed on the FPCM, which remarkably reduces the autopilot load. The dimensions of a homemade autopilot that is separately installed in the fuselage are 35x20x12mm with the weight of 6g. Through experiments of real flights, the turning, climbing, maneuverability and wind resistant ability of the MAV are tested. The flight results show that the MAV can fly with good stability and maneuverability.

***Keywords*—Micro Air Vehicle, flexible wing, aerodynamics, flexible printed circuits membrane, autopilot**

I. INTRODUCTION

The concept of Micro Air Vehicles (MAVs) has gained increasing interest over the past few years, with its primary goal being carrying out such missions as surveillance and measurements in situations where larger vehicles are not practical or too expensive. Such missions always involve low-altitude operations in battlefield, urban, frontier, thruway, photography, weather service, or wildlife applications. Payloads may consist of video cameras, aerograph, chemical sensors and communication devices [1].

There is a large body of existing and emerging research on various classes of micro air vehicles. Numerous technical challenges exist in designing and developing very small flying vehicles including mitigating the precipitous reduction in aerodynamic efficiency at low Reynolds number, satisfactory management of environmental disturbances such as wind gusts, efficient and reliable sensors design and installation for flight control. The above challenges are bringing in several hot research topics in the MAV area:

1) Numerical optimization and wind-tunnel testing on the micro air vehicle aerodynamics at the low Reynolds numbers.

MAVs generally employ a low-aspect ratio (LAR) design wing, which is characterized by a three dimensional flow field. Mueller's group [2,3] proved the importance of camber and wing shape by experimental investigation, indicating that cambered plates offer better aerodynamic characteristics and performance; when the aspect ratios is less than or equal to 1.0, rectangular and inverse Zimmerman platforms are generally most efficient, especially at Re=100,000. It also appears that the trailing-edge geometry of the wings and the turbulence intensity in the wind tunnel do not have a strong effect on the lift and drag for thin wings at low Reynolds numbers. Zhan's experimental research [4] found that sweepback angle had strong effects on the value of roll moment and yaw moment. Sun's wind tunnel results [5] showed that the triangle wing airfoil appeared to have greater maximum lift coefficient and fewer occurrences of vortex and turbulences. All these information is very useful for the micro air vehicle design.

2) Flexible wing design for the management of environmental disturbances.

Gust disturbances tolerance would be a crucial performance for low-inertia, low-maneuverability MAVs. It was introduced by Ifju's group [1, 6-7] that a flexible wing could provide benefits such as passive flow control, and adaptive washout for gust suppression. Flexible wings utilizing membrane materials are similar to natural flyers such as bats and insects. Compared with a rigid wing, a membrane wing is able to adapt well to the stall and has the potential to morphing to achieve enhanced agility and storage consideration [6]. To understand membrane wing's performances, its deformation and its benefit, Ifju utilized numeric calculation [7] and wind tunnel experiments integrated with a visual image correlation (VIC) system which measured the three-dimensional wing surface displacements and stress [1]. Also, The US Air Force Research Laboratory [8] has developed a MAV with a flexible wing for US Air Force Special Tactics Teams. And the flexible wings can be folded, allowing storage of the MAV in a compact tube.

3) Validation of technical integration of specific sensors used in MAV's autonomous flight.

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The low payloads of MAV make the small and light micro-electromechanical system (MEMS) devices the primary and favorable selections for its electric hardware design. Micro Pilot Company [9] and Brigham Young University [10] designed and built an autopilot consisting of Inertial Navigation System (INS) and Global Position System (GPS) based on MEMS device. University of Florida utilized statistical algorithm to detect vision-based horizon [11]. The bank angle and the pitch angle critical for stability and automatic control could be derived from a line corresponding to the horizon as seen from a forward facing camera on the aircraft. Optic flow sensors gaining information on incoming obstruction and altitude were also integrated into system to avoid possible collisions so that MAVs could autonomously fly in near-Earth environments such as forests, caves, tunnels and urban structures [12]. Air speed, the angle of attack and the slip angle are fundamental parameters in the control of aircraft, which are especially useful to identify wind direction and adapt the vehicle to the wind by positive control. Our previous work revealed that these flight parameters could be inferred from multiple hot-film flow speed sensors mounted on the surface of the wing [13].

This paper presents an electrically powered Micro Air Vehicle with a flexible wing integrated with on-board electronics. The configuration, manufacturing process, wind-tunnel test of the MAV prototype and its onboard electronics are introduced respectively. A real flight test is performed to validate the stability and maneuverability of the MAV. The merits of the MAV include: 1) The MAV has a flexible wing so it is adaptable to windy condition; 2) The wing is incorporated with electronic components by using a flexible circuit board as the skin; 3) Multiple flight parameters can be acquired by the aid of the onboard hot-film flow speed sensor array; 4) A small homemade MEMS-based embedded autopilot helps to enhance the performance of the MAV.

II. MICRO AIR VEHICLE

A. Flexible wing design

Fig.1 illustrates a novel MAV prototype built in Tsinghua University that has a flexible wing on which printed circuits are integrated. Unidirectional carbon fiber tape is cut into long narrow tacky strips with which the MAV's wing skeleton is constructed. The particular shape adopted here, called the "Zimmerman", is formed by joining two half-ellipses. The root chord length (the distance from the leading edge to the trailing edge at the center of the wing) and some other geometrical parameters are listed in Table I. Of critical importance in the design of low Reynolds number airfoils is the upper-surface pressure distribution [3]. The tendency of the flow to form a laminar-separation bubble can lead to a significant degradation in performance owing to the high bubble drag. To mitigate these adverse effects, a transition ramp in the pressure distribution is often employed to bring the flow to a gradual transition form in a thin bubble without a large pressure rise and high drag associated with an otherwise thick bubble. The airfoil is usually designated as S5010, which is the representative for a flying wing in MAV [14, 15]. We use the mean camber line of S5010 as the profile of the thin wing. To avoid burbling arising around the leading edge of the MAV, a woody fairing (see Fig.1) is added on the leading edge. After the skeleton with the airfoil is done, the top surface is coated with a Flexible Printed Circuits Membrane (FPCM), on which some sensors and electronic components are located.

Table I Flexible wing's geometrical parameters

Subsystem	Quantity	Unit
Wing platform area S	51800	mm^2
Mean aerodynamic chord	172	mm
Root chord length	217	mm
Wingspan	300	mm
Aspect ratio	1.75	-

Table II Mass of the MAV

Subsystem	***Mass[g]***
Flexible wing	27.5
fuselage	14
Brushless Motor, Propeller	16
2 actuators	7.5
Receiver	12.5
Electronic Speed Controller (ESC)	4
Autopilot	6
Battery	40
Wire and others	1.5
Total	129

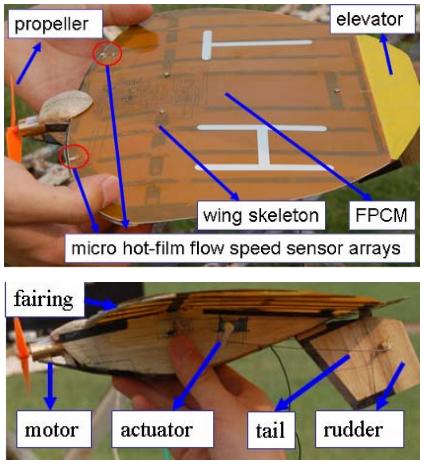

Figure 1 MAV with a flexible wing integrated with electronic components.

B. Propulsion system design

Two kinds of propulsion system –the internal combustion engine and the electric motor, are commonly used for MAVs. Though the former provides better thrust-weight ratio than the electric motor, it suffers from large vibrations and big noise, as well as the gravity center shift due to fuel consumption during the flight. However, the electric motor is more favorable because it is quieter and introduces lower vibration. Brushless motor generates higher torque than a brush motor with the same size, so it has the inherent capability to spin faster (around 21000r/min), and thus produces more power without deteriorating the performance at high currents and temperatures. Flight duration is mainly dependent on a battery's performance. It is better to utilize a battery with light weight, high capacity and high energy density (Wh/kg). Lithium-Polymer battery is the best choice for the MAV because of its high energy density, low cost, and rechargeable characteristics.

C. Fuselage design and payload's distribution

Major components, including autopilot, that guarantee the mission functionality are generally enclosed in the fuselage. The fuselage is now made up of wood board (carbon fiber stamper will be used in the future) and needs to be constructed to be robust against exerted stresses from demanding flying conditions, hard landings, and minor damages, especially when it is designed without landing gear in order to reduce overall weight and drag. Of critical importance in the process of the fuselage fabrication is retaining its symmetry to avoid sideslip, an accurate shape of upper edge for keeping the wing's airfoil, and a streamline shell for minimizing fuselage's drag. In the specific cross sections of the fuselage, wooden transverses with different sizes of isosceles trapezium are installed, as showed in Fig. 2, which are used for forming the fuselage's shape and also for strengthening it.

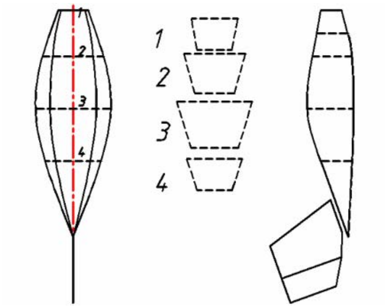

Figure 2 The fuselage structure configurated by 4 isosceles trapeziums.

The flight test has proved that the control of the longitudinal and lateral movements via manipulating left and right ailerons would weaken MAV's maneuverability and controllability because of the small and flexible wing. In order to improve the maneuverability, we utilize an elevator to control longitudinal movement and a rudder to control lateral movement. A large vertical tail can improve rolling dynamic performances, but then the MAV maybe easily disturbed by crosswind if the area of the tail is too large. Therefore a tradeoff between the shape and area should be determined through a calculation and flight tests with specific MAVs.

Furthermore the payload's distribution in the fuselage mainly affects the position of Center of Gravity (CG, which is crucial for longitudinal stability. To achieve a stable flight, the CG generally needs to be in the front of the Aerodynamic Center (AC), otherwise it would result in a nose-up attitude and make hard the longitudinal control of the airplane, or in the worst case make the MAV fall. The mass distribution is shown in Table II.

III. AERO DYNAMICS AND WIND TEST

To understand the aerodynamics of the flexible wing and establish a mathematic model for the MAV, low Reynolds wind tunnel experiments are performed. The established model can be used for flight simulation and control design of the MAV. The comparing experiments by using a rigid thin wing at the same size and shape are also performed for highlighting the distinct aerodynamic advantages of the flexible wing. Fig. 3 shows the flexible wing and rigid wing used in experiments.

The wind tunnel test is conducted in a low speed wind tunnel with a steady wind speed in the range of 5m/s ~ 20m/s. A six-component (three forces and three moments), sting balance are used for measuring aerodynamic forces (lift, drag, side) and moments (roll, pitch, and yaw). Fig.4 illustrates the experiment set-up of a rigid wing MAV installed in the wind tunnel. The same set-up is used for testing the flexible wing MAV. The sting balance is attached to a pitch-adjustable arm which is used to set model AOA (angle of attack).

Figure 3 The flexible wing (upper) and the rigid wing (below) with the same shape and the same size. Rigid wing is made by hard wood, strengthened by rib, and with a thickness of 1.5mm.

The results of the experiments, as shown in Fig.5, indicate that the flexible wing usually has a larger angle of stall, as well as has a larger maximum lift coefficient [6]. In this experimental model, for a given AOA, the lift coefficient of the flexible wing is slightly larger than that of its rigid counterpart. This is thought to be a function of two competing factors. The passive deformation along the trailing edge of a flexible wing, termed as "adaptive washout," decreases the local angle of attack along the wing, and thus enlarges the angle of stall. However, the deformation by lift load takes the hinge up while the elevator join stops the elevator from following up. Contrarily, elevator is slightly down, pretty much like the flap which is usually attached to an airplane wing's trailing edge to increase lift or drag. The camber of a flexible wing increases with wing deformation, which increases lift as well as drag. So the lift-drag ratio of the flexible wing varies in a complex way, as shown in Fig. 6. At smaller AOA, the lift-drag ratio of the flexible wing is larger than that of the rigid one. At larger AOA, as drag increases more quickly than the lift growth, the lift-drag ratio of the flexible wing becomes smaller than the rigid one.

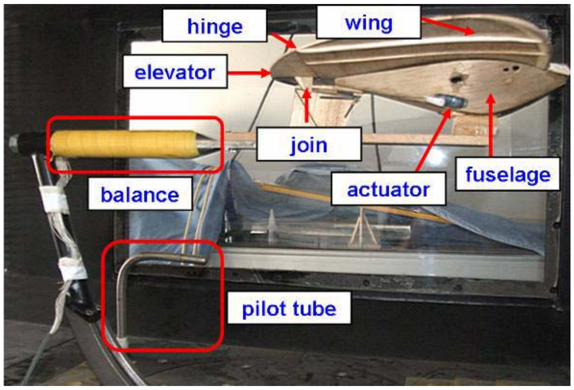

Figure 4、The rigid wing is mounted in. a Low Reynolds wing tunnel with balance and pilot tube. Elevator is connectting with servo

The slope of the lift curve as seen in Fig. 5, which is an important factor [1] associated with the wing's capability to handle vertical gusts (or similar environmental disturbances), is found to be lower for the flexible wing. This is an indication of the adaptive washout built into the wing for gust alleviation. In addition, a deformable wing is expected to harvest an intrinsic benefit: a portion of the energy that would normally be lost to the wing-tip vortices and wake, downstream of the MAV, now is stored as elastic strain energy in the wing's structure, which has been proved to be a well known advantage exploited in biological systems [1].

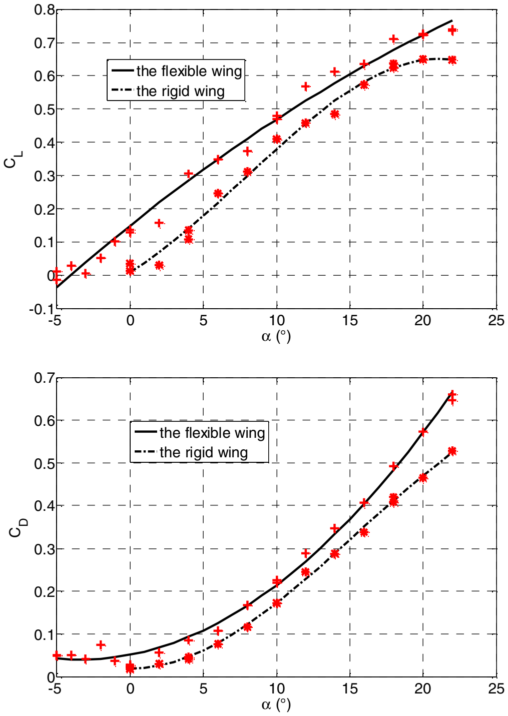

Figure 5 Lift coefficient (Upper) and drag coefficient (Lower) versus angle of attack (α) at Re=100,000. The solid line (a polynomial fit of experimental data indicated by "+") is the measurement for the flexible wing, and the dashdot line (a polynomial fit of experimental data indicated by "*") is the measurement for the rigid wing.

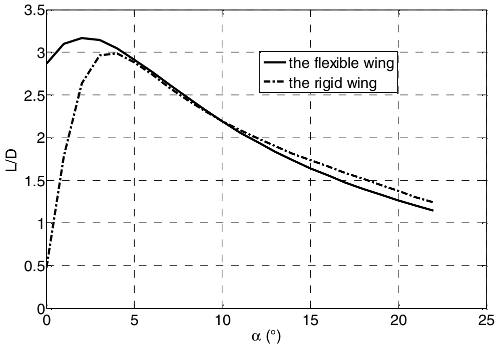

Figure 6 Lift-to-drag ratio for flexible wing model (solid line) and for rigid wing model (dashdot line) at Re=100,000. Using polynomial fit data's division to avoid sentus.

IV. ON-BOARD ELECTRONIC DEVICES

The criteria of selecting onboard electronic components used in the MAV include small size, light weight, low consumption, multifold function, convenient connections with other equipments, good stabilization and reliability during flight, and low cost. Fig.7 shows the block diagram of on-board electronic devices. Phase Locked Logic (PLL) synthesized 7 channels Pulse Code Modulation (PCM) Receiver outputs Pulse-Width Modulation (PWM) signals related to throttle, rudder, elevator, gear and other commands to the autopilot. Bases on control theory and given flight commands, the autopilot outputs PWM signals to drive the Electronic Speed Controller (ESC) and actuators. ESC controls the speed of motor and the actuators to drive the elevator and rudder.

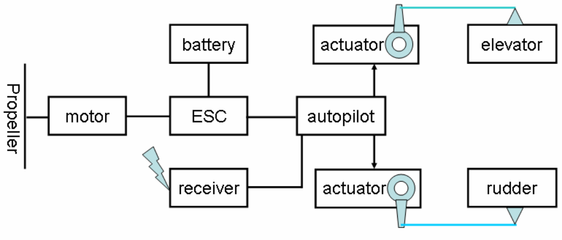

Figure 7 Block diagram of on-broad electric devices.

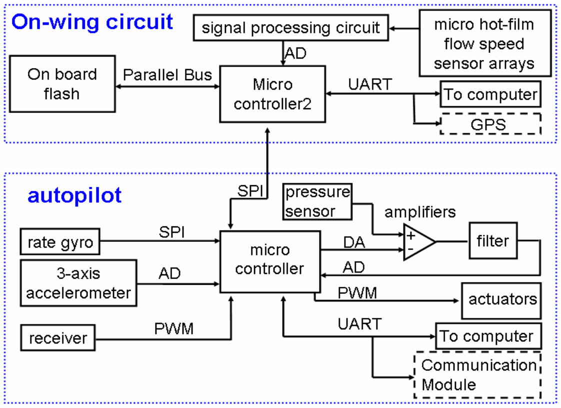

Figure 8 Block diagram of the core control hardware system composed of On-wing circuit and autopilot.

The core control hardware system is comprised of two parts, namely On-wing circuit and autopilot, as shown in Fig 8. The On-wing circuit is printed on a FPCM which also serves as the skin of the wing. All FPCM components are attached under the wing and covered by the fuselage, so that they would not affect the airflow around the surface of wing and be protected by the fuselage. Three flight parameters—air speed, angle of attack and angle of sideslip, are determined by the aid of micro hot-film flow speed sensor arrays distributed on the front edge of the MAV wing, as illustrated in Fig.9 (left). The readings of the sensors are acquired and converted into digital signals that are the inputs of the signal processor, whose outputs deduce the flight parameters based on micro controller2 processing. More details about hot-film flow speed sensors and the methodology to obtain flight parameters can be found in [13]. The micro controller2 on FPCM send the readings of flight speed, attack of angle, slip angle to autopilot through serial peripheral interface (SPI), and these sensor data are fused with other data like angular rate, acceleration, altitude, control commands, and etc. in autopilot. All data can be recorded by using an on-board flash offering 32Mx8bit, NAND cell, which is an optimum solution for flight log requiring non-volatility. The flight log can be used to analyze the performance of the MAV.

The schematic diagram of MEMS-based embedded autopilot is shown in Fig. 8, the circuit of which is printed on a hard Printed Circuit Board (PCB). Real-time data processing and output update are well improved by using two micro controllers for concurrent computation. Three micromachined gyroscopes with integrated serial peripheral interfaces (SPI) which transmit the digital data to micro controller, a micromachined 3-axis accelerometer, and a micromachined pressure sensor for measuring altitude, are integrated on the autopilot rather than on the FPCM because the flexible wing might be otherwise deformed and vibrated to downgrade the measurement accuracy of these sensors. The dimensions of our homemade autopilot are only 35x20x12mm, and the weight is 6g, as illustrated in Fig.9 (right). The small size and the light weight make it possible to install it in a compact fuselage while retaining a feasible CG position for the MAV.

In the future, communication module to transmit command and data between ground station and onboard system, and a GPS to acquire the latitude and longitude for MAV will be added in the control system. Their connection to the core control hardware system is shown in Fig.8 (marked by dashed frame).

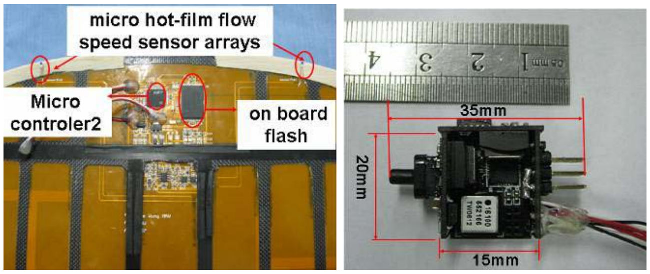

Figure 9 The real On-wing circuit (left) and micro autopilot (right).

V. IN-FLIGHT EXPERIMENTS

Flight tests are performed on the flexible wing MAV prototype in an open area using a radio controller (R/C) to operate the flight. The wind conditions throughout the flights range from calm to gentle breeze. After the MAV has been well trimmed, it is hand-thrown into the sky to reach an appropriate flying speed. Thereafter the MAV is manipulated by an operator standing on the ground using an R/C transmitter. The on-board sensors measure the corresponding information which is then transmitted to the on-board flash on FPCM and recorded.

Throughout the flight tests, the turning, climbing, maneuverability and wind resistant ability are all tested. The flight is shown in Fig.10. The rudder is used to generate lateral maneuvers, and thus generate the roll and yaw movements, as shown in Fig.11. In general, lateral maneuvers are particularly difficult because the MAV is so responsive [16]. Small levels of actuation can achieve roll rate about 100deg/s. But compared to the rigid wing, the flexible wing improves a lot. With the flexible wing, the roll rate reaches to the steady state in a short time, and it would enhance the lateral maneuvers. That is quite useful to resist gust wind. The elevator controls the longitudinal maneuver (see Fig.12), which alter the angle of attack and therefore alter the lift. Consequently, the MAV ascends or descends to achieve longitudinal maneuvers. 3-axes (along the aircraft's body axes) normal acceleration data are measured in the flight, as shown in Fig.13. Z-axis normal acceleration (a_z) fluctuates around 1g because of the Earth's gravity. Generally, the fluctuation of the acceleration along 3-axes is quite large due to MAVs' low-inertia, wind disturbance and vibration of the body. However the acceleration along 3-axes of the MAV with the flexible wing displays a smaller fluctuation (the RMS of the acceleration is smaller than 1g) when the MAV is hovering and disturbed by wind. The maximum flight duraton is more than 20 minutes.

Figure 10 The MAV is climbing (left) and turning (right)

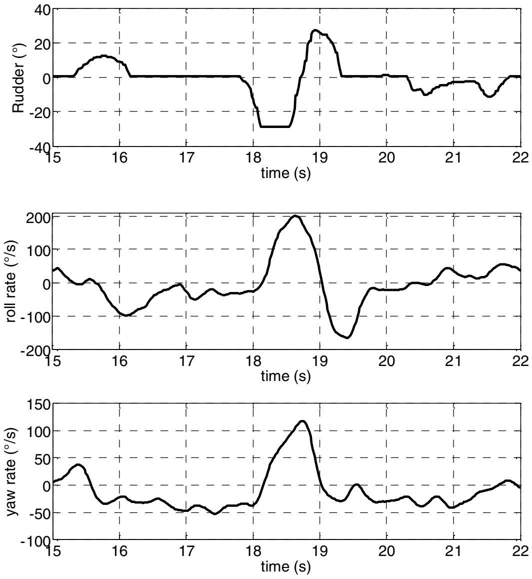

Figure 11 Typical turning action by controling the rudder. The rudder command (top), the corresponding roll (middle) and yaw movement (bottom) are illustrated, supposing that rudder turing left is positive direction, roll rate is along the x-axes in the aircraft's body axes, yaw rate is along the z-axes in the aircraft's body axes

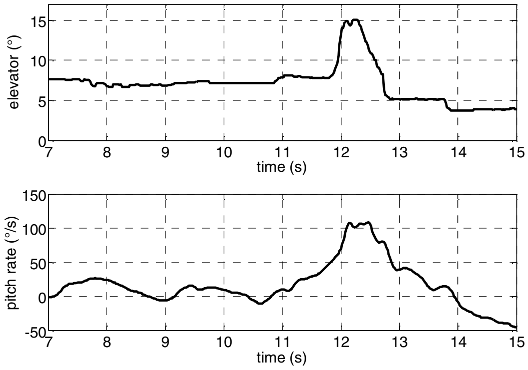

Figure 12 Ascending action by controling elevator. Elevator command (top) and the pitch rate (bottom) are illustrated, supposing that elevator turing up is positive direction and pitch rate is along the y-axes in the aircraft's body axes

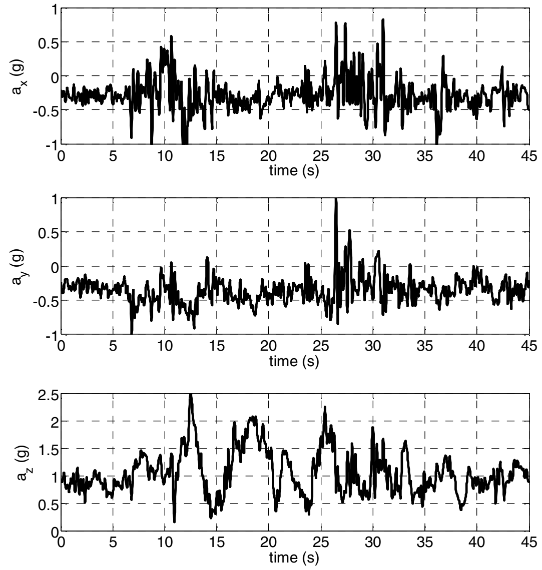

Figure 13 3-aixs normal acceleration along the aircraft's body axes while the MAV is cruising

VI. CONCLUSION AND OUTLOOK

An electrically powered MAV with a flexible wing integrated with on-board electronic components is presented in this paper. The low aspect ratio wing, adopting the airfoil of S5010 and Zimmerman shape, is made up of a FPCM covered with a thin carbon fiber skeleton. The FPCM serves as both the skin of the aircraft wing and a supporting substrate for the electronic components. The real MAV prototype is tested in a low-speed wind tunnel in order to evaluate its aerodynamic characteristics. The comparing experiments are conducted on a flexible wing and its rigid counterpart to corroborate the distinct aerodynamic advantages of the flexible wing. The results of the wind tunnel experiments indicate that the flexible wing has a larger angle of stall, bigger maximum lift coefficient than the rigid wing. However, the lift-drag ratio of the flexible wing varies in a complex way because the flexible wing also increases the drag with the growth of lift. Since most of signal processing circuits can be distributed on the FPCM, the load of the autopilot can be remarkably reduced. The homemade autopilot that is separately installed in the fuselage is very small with the size of only 35x20x12mm and weight of 6g. Through experiments of real flights, the turning, climbing, maneuverability and wind resistant ability of the MAV are all tested. The flight results show that the MAV can fly with good stability and maneuverability.

Our future work will focus on the automatic control of the MAV to achieve a fully autonomous flight without human interference. The angle of attack and slip angle that are extracted from hot-film flow speed sensors will also be used in the flight control to improve the MAV's adaptability in windy condition.

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REFERENCES

[1] R.Albertani, B.Stanford, J. P. Hubner, P. G. Ifju, "Aerodynamic Coefficients and Deformation Measurements on Flexible Micro Air Vehicle Wings ," Experimental Mechanics, vol. 47, no. 5, pp. 625–635, 2007.

[2] Pelletier, Alain; Mueller, Thomas J. "Low Reynolds number aerodynamics of low-aspect-ratio, thin/flat/cambered-plate wings," Journal of Aircraft. vol. 37, no. 5, pp. 825-832 , 2000

[3] Thomas J.Mueller. Fixed and Flapping Wing Aerodynamics for Micro Air Vehicle Applications. The American Institute of Aeronautics and Astronautics. Inc, 2001, pp.115–141.

[4] Zhan Jing-Xia, Wang Wei-Jun, Wu Zhe, Wang Jin-Jun."Wind-tunnel experimental investigation on a fix-wing micro air vehicle," Journal of Aircraft, vol.43, no.1, pp. 279–282, 2006

[5] Sun Dong, Wu Huaiyu, Zhu Rong, Hung Ling Che, "Development of micro air vehicle based on aerodynamic modeling analysis in tunnel tests," Proceedings of the 2005 IEEE International Conference on Robotics and Automation, pp. 2235–2240, April 2005.

[6] Shyy Wei, Ifju. Peter, Viieru Dragos, "Membrane wing-based micro air vehicles," Applied Mechanics Reviews, vol 58, pp. 283-301,2005

[7] B.Stanford,R.Albertani, P.G. Ifju, "Static finite element validation of a flexible micro air vehicle," Proceedings of the 2006 SEM Annual Conference and Exposition on Experimental and Applied Mechanics 2006, pp. 2142–2153.

[8] Deluca. Anthony M, Reeder. Mark F, Freeman. Jacob, Ol. Michael V, " Flexible- And rigid-wing micro air vehicle: Lift and drag comparison," Journal of Aircraft, vol. 43, no. 2, pp. 572–575, 2006

[9] R. Gardner, " MicroPilot- Getting bigger by being smaller", Aerospace International, vol.32, no.3, pp. 32–33, 2005

[10] R. Beard, D. Kingston, M. Quigley, D. Snyder, C.Reed, J. walt, "Autonomous vehicle technologies for small fixed-wing UAVs," Journal of Aerospace Computing, Information and Communication, n JAN, pp. 92–108, January 2005

[11] Todorovic. Sinisa, Nechyba Michael C, " A vision system for intelligent mission profiles of micro air vehicles," IEEE Transactions on Vehicular Technology, vol. 53, no. 6, p 1713-1725, November, 2004

[12] William E, Green and Paul Y. Oh, "A MAV That Flies Like an Airplane and Hovers like a Helicopter," International Conference on Advanced Intelligent Mechatronics, pp. 693-699, July 2005.

[13] Haiping Fei, Rong Zhu, Zhaoying Zhou and Jindong Wang, "Aircraft flight Aircraft flight parameter detection based on a neural network using multiple hot-film flow speed sensors," Smart Materials And Structures, vol.16, pp. 1239-1245, July 2007.

[14] P. Cosyn, P, J.Vierendeels, "Numerical investigation of low-aspect-ratio wings at low Reynolds numbers," Journal of Aircraft, vol. 43, n. 3, pp 713-722 , May/June, 2006

[15] M.E. Reid, Kozak Jeffrey, "Thin/cambered/reflexed airfoil development for micro air vehicle applications at reynolds numbers of 60,000 to 100,000," Collection of Technical Papers - 2006 Atmospheric Flight Mechanics Conference, pp 1467-1472, Aug. 2006.

[16] H. Garcia, M. Abdulrahim and R. Lind, "Roll Control for a Micro Air Vehicle using Active Wing Morphing," AIAA-2003-5347, August. 2003