Numerical Analysis of Piezoelectric Signal of PVDF Membrane Flapping Wing in Flight

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Abstract. As an organic piezoelectric material, polyvinylidene fluoride (PVDF) can be utilized to fabricate thin film with high mechanical properties, and this film can be used to form flapping wing membrane. This type of wing with piezoelectric effect can solve the problems of the flight conditions measurement of flapping-wing micro aerial vehicles (FMAVs) in practical flapping flight. This study focuses on analysing the voltage outputs generated by PVDF membrane, and proposes two output voltage signal characteristics that can be used to deduce the flight conditions of FMAV, i.e. the voltage wave scale and voltage wave phase difference. The linear plate theory and unsteady aerodynamics coupling with piezoelectric equation are adopted to calculate the voltages generated by inertia and aerodynamic forces. The reasons and applications of scale and phase difference are analysed and discussed, and practical examples are demonstrated to illustrate specific impacts on these two signals.

1. Introduction
The flapping-wing micro aerial vehicles (FMAVs) is considered as an important trend of MAV by many researchers. There are many prototypes now designed and tested. The usual testing method for FMAVs uses force balance, which can measure both thrust and lift forces [1]. However, in FMAVs testing, it is impossible to consider the plunge and pitch motions of real flight, and real flow velocity make great difficulties to simulate. For example, it is difficult to measuring the lift and thrust force during in complex flapping flight, because flapping wing has untraditional flight mechanisms. The other way which can measure FMAVs performances uses sensors on aircraft, but traditional overweight general sensors cannot be directly mounted on FMAVs. According to above limitations, some researches focused on finding suitable sensors for FMAVs. One solution proposed is using piezoelectric materials (PZT) to measure the total lift and thrust forces. PZT can directly transform mechanical energy to electrical signal without complex circuit, so the sensors made of PZT can be lightweight and small enough, and the recorded electrical signal during flight can be used to infer the resultant force.

As one type of the piezoelectric materials, polyvinylidene fluoride (PVDF) membrane is wildly used as the core part of sensors. It can also harvest the energy from the air flow, and the capability of energy harvesting was investigated by Orrego et al. [2]. An equipment for wind power collecting was made of PVDF membrane, following with a wind tunnel test to measure the value of electrical outputs. They found that the inverted-flag configuration adopted can maintain the flutter motion in a wider range of wind speed, and the flutter boundary can be changed by tailoring the length-width ratio. The conclusions show that PVDF can transform the energy from airflow to electrical voltage which can be read from oscilloscope, and the outputs can be influenced by the variation of external factors.
Furthermore, it can be directly utilized to fabricate membrane wing due to the high-quality mechanical properties of PVDF membrane. Then PVDF film cannot only be used to build the wing of FMAVs, and also measure in-flight force-induced electrical signal by itself. The application was used by yang et al. [3]. They fabricated a FMAV, and one of its membrane of wings was made of PVDF-parylene composite. The PVDF membrane wing can export the electrical signal, and this signal can calculate out the flapping lift and thrust forces. A wind tunnel test was made to collect flight data, and the calculated lift and thrust results from left PVDF wing were compared with data measured from right wing. This comparing can verify the correctness of theory analysis and calculation.

All of researches above demonstrated that PVDF membrane can be a multifunctional component for FMAV. It can be used to form the wing as well as the sensor to detect the aerodynamic force encountered. In this research, a PVDF membrane with carbon fibre (CF) rods wing configuration is built, and following with the model using linear plate theory and unsteady aerodynamics coupling with piezoelectric equation. The application was used by yang et al. [3]. They fabricated a FMAV, and one of its membrane of wings was made of PVDF-parylene composite. The PVDF membrane wing can export the electrical signal, and this signal can calculate out the flapping lift and thrust forces. A wind tunnel test was made to collect flight data, and the calculated lift and thrust results from left PVDF wing were compared with data measured from right wing. This comparing can verify the correctness of theory analysis and calculation.

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2. Structure and Aerodynamic Model

In nature, the flight mode and motion of birds and insects are always the combination of wing flapping, twisting, folding and gliding. These flying movements are executed by their muscular activity. However, it is too complicated for FMAVs to simulate, because these multi-degree motions need a sophisticated mechanism to fulfil, and such mechanism can bring massive weight penalty. Therefore, the mechanism of FMAVs should be simplified. Traditional simplified flapping wing is set to have two-dimensional [4]. The two-dimensional motion of flapping wing is usually combined of a plunging flapping and a pitching twisting. Note that the pitching motion can be passive, i.e. flexible deformation of flapping wing in chordwise direction. The flow-structure interaction of this passive flexible pitching motion was investigated by Heathcote [5]. The analysis was carried out for 9,000 to 27,000 Reynolds numbers. The flexibility in chordwise direction was found to increase both thrust coefficient and propulsive efficiency. The skeleton arrangement and the twisted stiffness of membrane flapping wing can affect the thrust producing. Larger thrust can enhance flight performance, so the ability of thrust generating is very important for flapping wing. Wu et al. [6] conducted experimental studies on the aerodynamic influences of flapping wing flexibility. The wing skeleton are flexible, and all types of the skeleton arrangements are based on the same membrane wing profile. A single-degree-freedom mechanism was adopted in experiment, and tested under different flapping frequencies. By comparing the thrust and wing surface displacement of membrane wings, the optimal skeletal wing structure was revealed and explained. The stiffness of wing skeleton also plays a key role in thrust production of flapping wing, and it is proved by Mazaheri et al. [7]. A serious of flexible membrane flapping wings were formed, and these wings have the same geometrical characteristics, but their twist stiffness are different due to stiffened carbon-fibre ribs. These ribs are arranged to have inconsistent diameters, so as to change the flexibility of wings. Experiments are made to test the thrust of wings with various flapping frequencies. Combining the results of above researches together, it is demonstrated that the maximum lateral displacement should be at the trailing edge, and the moderate twist stiffness of flapping membrane wing can produce thrust more efficiently.

2.1. Structural Model

The skeleton of membrane wing can use the carbon fibre rods, demonstrated by [5-7]. The structure at leading edge is arranged a carbon fibre rod, and boned with wing membrane. Two thinner carbon fibre rods are used to reinforce the membrane in chordwise direction. Such configuration can make sure the rigidity of the leading edge as well as adequate flexibility of trailing edge.

This type of wing model can be established based on the bending motion equation of Von Kármán large deflection equation. The equation of motion of the membrane wing is

\[ M\ddot{w}(x, y, t) + C\dot{w}(x, y, t) + K\dot{w}(x, y, t) = L_E \]  

(1)
where $M$, $C$ and $K$ are the mass, damping and stiffness matrix; $w$ is the displacement at wing surface location $x, y$ at time $t$; $L_E$ is the aerodynamic force matrix.

The inertia force due to the motion of mechanical movement is given by

$$F_i = \omega^2 \beta_{\text{max}} \cos(2\pi \omega t + \phi) \sum m_ir_i$$

(2)

where $\omega$ is the flapping frequency; $\beta_{\text{max}}$ is the maximum flapping angle; $\phi$ is the initial flapping phase; $m$ and $r$ are the mass and the rotation radius of $i$th structural finite element.

2.2. Aerodynamic Model

The unsteady aerodynamics can use the panel method [8]. The aerodynamic generalized force is calculated from

$$L_{E_j} = \rho V_\infty \iint \Delta P dx dy$$

(3)

where $\rho$ is the air density; $V_\infty$ is the flight speed; $\Delta P$ is the pressure force; $j$ is the panel number.

2.3. Piezoelectric Coupling Equation

Combining equations (1)-(3), a generalized form of the piezoelectric coupling equation is [9]

$$M \ddot{U} + C \dot{U} + Ku - \Theta V = L_E + F_i$$

$$cv + \frac{V}{R} + \Theta^T \dot{U} = 0$$

(4)

where $U$ is the vector describing the structural states; $\Theta$ is the piezoelectric coefficient matrix; $V$ is the piezoelectric voltage output vector; $C$ is the equivalent piezoelectric capacitance matrix; $R$ is the applied load resistance; $O$ is the zero matrices.

3. Results and Discussions

The results in this research are from the one side of PVDF membrane wing. The geometric and material properties of the wing membrane and skeleton are given in Table 1 and Figure 1.

Results in Figure 2 shows the time-history analysis of the flapping wing model outputs in two periods. The flow speed is set to 4 m/s when FMAV in forward flight; The flapping frequency of the wing is 20 Hz; The flapping angle is $\pm 60^\circ$; and the angle of attack is $20^\circ$; the load resistance in the electrical circuit is $1 \times 10^5 \, \Omega$.

Figure 2a shows the tip displacement at leading edge of the wing during flapping. The tip displacement of flexible wing structure is smaller than hypothesis rigid wing. Figure 2b shows the maximum variation of attack angle. The maximum scale of attack angle is nearly at 3/4 spanwise length because of the arrangement of flapping wing structure. Figure 2c shows the voltage output of PVDF membrane wing. The voltage output reaches the millivoltage level. Figure 2d demonstrates the variation of angle of attack at wing tip.

Table 1. Material parameters of PVDF membrane wing.

| Parameter                  | Value          |
|---------------------------|----------------|
| Elastic modulus of FVDF   | $0.03 \times 10^{11} \, \text{Pa}$ |
| Density of PVDF           | $1780 \, \text{kg/m}^3$ |
| Poisson ratio of PVDF     | 0.35           |
| Piezoelectric constant (d31) | $-0.18 \times 10^{-10} \, \text{m/V}$ |
| Permittivity constant     | $88.54 \times 10^{-11} \, \text{F/m}$ |
| Elastic modulus of CF rod | $1.10 \times 10^{11} \, \text{Pa}$ |
| Density of CF rod         | $1800 \, \text{kg/m}^3$ |
| Poisson ratio of CF rod   | 0.31           |
Figure 1. Geometric and components parameters of PVDF membrane wing.

Figure 2. The time-history analyses of (a) tip displacement versus the period; (b) maximum variation of attack angle versus the period; (c) the voltage output versus the period; (d) attack angle variation of the wing tip versus the period for PVDF membrane wing.

Figure 3 shows the voltage outputs generated by PVDF membrane wing. The operation condition is as the same as above. The total voltage output can be separate by the contributions of aerodynamics and inertia force. It can be seen that most of the voltage in circulate is produced by inertia force, and the contribution of aerodynamic force is quite small. The summit of total voltage is +14.46 mV, which is equal to the inertia force voltage +13.89 mV plus aerodynamic force +0.57 mV at the same time step. Note that the average aerodynamic force induced voltage is higher than 0 V. And also, there has a phase difference between inertia and aerodynamic force voltages, i.e. nearly a quarter period. These offsets are influenced by the attack angle. Thus, the phase of total voltage output is advanced slightly than the voltage inertia force induced, and the scale of total voltages are not symmetric about zero-voltage-axis.

Figure 4 shows the total voltage outputs of PVDF wing under various flapping frequencies, and other operating conditions keep the same in figure 2. It is obvious that the higher flapping frequency rises, the larger the scale of generated voltage expands. There also have phase differences between voltages in different frequencies, which are explained in the describe of figure 3. The phase advance of 15 Hz voltage is 2.5% period higher than mechanical or inertia force voltage period; for 20 Hz and 25 Hz are 1.2% and 0.5% period higher, respectively. These phenomena demonstrate that lift and thrust forces, caused by the increase of flutter frequency, are not only reflected in the amplitude of PVDF membrane voltage output, but they can also be shown in the phase difference of voltage output.

Figure 5 shows the voltage outputs of PVDF membrane wing under various flight speed of FMAV. The operating conditions are as above. Form the curves, With the rising of flight speed, the extension
of induced voltage does not increase apparently, because the voltage induced by aerodynamics has quiet small proportion of the total voltage output. The largest voltage is 14.68 mV, generated in 6 m/s flight speed, and it is only 2.94\% higher than the voltage at 2 m/s. Such a small voltage increase under different flight speeds can cause the error amplification of PVDF membrane sensor. The measurement of phase difference can be an assistant method to reduce the measurement error of the voltage. In figure 5, the phase advance is increase as the flight velocity grows. The total voltages are equal to changing aerodynamic induced voltage plus unchanged inertia induced voltage, and the phase of aerodynamic voltage is a quarter period higher than inertia, then the phase differences of total voltages exist. When flight speed is at 6 m/s, the phase is advanced 1.6\% period than 2 m/s speed, 2.0\% period than mechanical input period.

Figure 3. Voltage output contributions of PVDF membrane wing.

Figure 4. Voltage output of PVDF membrane wing under various flapping frequencies.

Figure 5. Voltage output of PVDF membrane wing under various flight speeds.
4. Conclusion
In this paper, a FMAV with PVDF membrane wing is proposed. This type of wing cannot only serve as a component of wing structure, and it also can be a sensor to detect the flight conditions based on the piezoelectric effects. The output that can be used to deduce the flight conditions is deduced voltage, and the data of voltage that can be directly use is the amplitude of voltage wave. Another method to measure the flight conditions is the phase advance of voltage wave. The phase of inertia force induced voltage lags a quarter phase than aerodynamic force induced voltage, so the sum of them, i.e. total voltage, has slight of phase change due to the variation of aerodynamics. This phenomenon can also be an auxiliary method to fix the measurement error.

References
[1] Percin M, Oudheusden B W V, Croon G C H E D and Remes B 2016 Force generation and wing deformation characteristics of a flapping-wing micro air vehicle ‘delfly ii’ in hovering flight Bioinspir. Biomim. 11 (3) 036014
[2] Orrego S and Shoele K 2017 Harvesting ambient wind energy with an inverted piezoelectric flag Appl. Energ. 194 212-222
[3] Yang L J, Hsu C K, Ho J Y, and Feng C K 2007 Flapping wings with pvdf sensors to modify the aerodynamic forces of a micro aerial vehicle Sensor Actuat. A-Phys. 139(1-2) 95-103
[4] Buchmann N and Radespiel R 2014 Computational three-dimensional flapping-wing analysis AIAA. J. 52 (1) 203-206
[5] Heathcote S, Wang Z and Gursul I 2008 Effect of spanwise flexibility on flapping wing propulsion J. Fluid. Struct. 24 (2) 183-199
[6] Wu P, Ifju P and Stanford B 2010 Flapping wing structural deformation and thrust correlation study with flexible membrane wings AIAA. J. 48 (9) 2111-2122
[7] Mazaheri K and Ebrahimi A 2010 Experimental investigation of the effect of chordwise flexibility on the aerodynamics of flapping wings in hovering flight J. Fluid. Struct. 26 (4) 544-558
[8] Long L N and Fritz T E 2004 Object-oriented unsteady vortex lattice method for flapping flight J. Aircraft. 41 (6) 1275-1290
[9] Li D, Wu Y, Da Ronch A and Xiang J 2016 Energy harvesting by means of flow-induced vibrations on aerospace vehicles Prog. Aerosp. Sci. 86 28-62