Numerical Investigations on Aerodynamic Forces of Deformable Foils in Hovering Motions

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Abstract. The aerodynamic effects of wing deformation for hover flight are numerically investigated by a two-dimensional finite-volume (FV) Arbitrary Langrangian Eulerian (ALE) Navier-Stokes solver. Two deformation models are employed to study these effects in this paper, which are a full deformation model and a partial deformation one. Attention is paid to the generation and development of the leading edge vortex (LEV) and trailing edge vortex (TEV) which may illustrate the differences of lift force generation mechanisms from those of rigid wings. Moreover, lift coefficient Cl, drag coefficient Cd, and figure of merit, as well as energy consumption in hovering motion for different deformation foil models, are also studied. The results show that the deformed amplitude, 0.1*chord, among the cases simulated is an optimized camber amplitude for full deformation. The results obtained from the partial deformation foil model show that both Cl and Cd decrease with the increase of camber amplitude. It is found that the effect of deformation in the partial deformation model does not enhance lift force due to unfavorable camber. But TEV is significantly changed by the local AOA due to the deformation of the foil. Introduction.

1. Introduction
In the last decade, attention has increasingly been paid to the aerodynamics of deformable wings[1-10] due to the rising popularity of micro air vehicles (MAVs). Researchers have gradually obtained systematic and deep insights into unsteady aerodynamic forces on rigid wings[11-18]. With those insights obtained, further research on flexible wings found in nature and their lift generation mechanisms is expected. However, the structures and materials of flexible wings are found to be so complex that so far one could not yet find simple and accurate models to represent major wing features by measurement data or regression fitted values. Therefore, the prescribed deformation models are adopted in this paper to investigate this problem, which can be considered as semi-rigid wing models because wing deformation is prescribed with simplified harmonic equations during wing flapping based on experimental data. Hovering flight mode is employed where the body is assumed to be fixed in space and the freestream velocity is zero[1,3,11]. As for deformable wings, the hovering
motion is considered as a combination of three components: translation, rotation as well as deformation, respectively. And in order to understand the effect of wing flexibility on the aerodynamics of flapping motion, two types of deformable foil models can be used for the purpose of experiment and numerical investigation. They are full deformation foil models [4, 19, 20] and partial deformation ones.

2. Mathematics
The incompressible unsteady Navier-Stokes governing equations, modified by the Artificial Compressibility Method (ACM) with dual-time steps and Arbitrary Langrangian Eulerian (ALE) Method in non-dimensional vector form are used to simulate the flapping aerodynamics. And the solution methods, including discretization strategy and numerical schemes, as well as model validation for the above ALE governing equations, have been described in detailed by Su et. Al. [21], which will not be repeated in this section.

3. Results and Discussions
In this paper, all 2D foil models mentioned above in section one are used to investigate the effects of foil deformation on lift force generation mechanisms. The shape equations of full and partial deformation foil models are described as follows:

\[
\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1
\]

where \(a\) and \(b\) correspond to the major and minor axes of ellipse. \(x\) and \(y\) mean horizontal and vertical coordinate, respectively. In this paper, the ratio of long axis to short one is set to 30:1.

3.1. Models of the full and partial deformation foils
Translation and rotation motions as well as wingbeat frequency are set to be the same as our previous work for rigid wing investigation [21] for the purpose of comparison. As for the full deformation foil, the deformation of camber is introduced to the central line of the foil and the whole foil deforms accordingly (See figure 1(a)). In general, two quadratic functions are adopted to represent the camber shape of the central line of the foil for the full deformation foil model as follows:

\[
\begin{align*}
    y_c &= \frac{m(t)}{p^2} [2p \frac{x}{c} - \left(\frac{x}{c}\right)^2 ] & (0 \leq \frac{x}{c} \leq p) \\
    y_c &= m(t) \left[ (1-2p)^2 + 2p \frac{x}{c} - \left(\frac{x}{c}\right)^2 \right] & (p < \frac{x}{c} \leq 1)
\end{align*}
\]

where \(x\) means the abscissa of a point on the chord, \(y_c\) is the deviation of the mean line, and \(m\) the maximum of the deviation which is called the maximum camber, here \(p\) is set to 0.5.

As for the partial deformation foil model, which is one-quarter rigid and the rest flexible, only one quadratic function is adopted to represent the camber shape of the mean line as follows:

\[
\begin{align*}
    y_c &= \frac{m(t)}{(1-p)^2} \left[ (\frac{x}{c})^2 - 2p \frac{x}{c} + p^2 \right] & (p < \frac{x}{c} < 1)
\end{align*}
\]

where \(pc\) is the value of the camber position along the foil, and \(m(t)\) in equation (2) and (3) are described as follows:

\[
m(t) = m_0 \sin(2\pi f_d t)
\]
where \( m_0 \) is the amplitude of the camber in time series. \( m_0 \) is set from 0 (rigid case) to 0.2*chord in the simulations[2,4], which is plotted in figure 1.

3.2. Results of the full deformation foil

In this subsection, the differences of aerodynamic forces in hovering motion of the deformable and rigid foils are to be studied. The kinematic parameters of the movement of the hovering foils are set as: \( A_0/c = 3.185 \), \( f_0 = 0.1 \), \( \phi = 0 \), \( Re = 100 \), and camber amplitude, \( m_0 \), varies from 0 to 0.2*chord. Based on the kinetic parameters mentioned above, the foil trajectory of the full deformation model is plotted in figure 2.

Figure 1. The sketches of full deformation foil model and one quarter rigid foil model.

Figure 2. The foil trajectory of the full deformation model.

Figure 3. The time-histories of lift and drag coefficients for various camber amplitudes in the full deformation model.

Figure 3 gives the time-histories of lift force coefficient \( (C_l) \) and drag force coefficient \( (C_d) \) of the fully deformable foil in one hovering motion cycle for different camber amplitudes. One can observe clearly that no matter how much camber amplitude is used, there are four crests and troughs for both the \( C_l \) and \( C_d \) curves. Based on our understanding of the lift force generation mechanisms for rigid wing in hovering motion, the first and the third crests appearing in Figure 3 are generated by the wake
capture mechanism[17-18], while the other two crests are generated by the delayed stall mechanism[15].

3.3. Results of the partial deformation foil model
The partial deformation foil model, which was proposed by Miao[22] to explore high lift force generation during insect flight, is investigated in this section by numerical simulations. The kinematic parameters of the hovering motion are same with the full deformations’. The trajectory of hovering motion for partial deformation foil model is plotted in Figure 4.

![Figure 4. The trajectory of hovering motion for partial deformation foil model.](image)

(a) Upstroke for partial deformation foil model (b) Downstroke for partial deformation foil model

Figure 5 shows the profiles of lift force coefficient (Cl) and drag force coefficient (Cd) of the partial deformation foil model in one hovering motion cycle for different camber amplitudes. Figure 5 shows that deformation leads to negative Cl difference values during the hovering motion cycle. This means that the deformation of the wing results in smaller lift force in the partial deformation foil model.

![Figure 5. The time-history of lift and drag coefficients for various camber amplitudes in partial deformation foil model test.](image)

(a) The time-histories of lift coefficients (Cl) (b) The time-histories of drag coefficients (Cd)

3.4. Energy consumptions for different models
Energy consumption is one of the most important considerations in the aerodynamic design of MAVs. The method for calculating energy consumption in the rigid model is to obtain the work which supports the foil to complete the hovering action[23] by using the formulae:

$$P = \int_0^1 C_d \left( \frac{\dot{f}}{T} \right) \* \dot{U} \left( \frac{t}{T} \right) \* d \left( \frac{t}{T} \right)$$

(5)

where $\dot{U}$ is the dimensionless velocity vector of the rigid foil and $\dot{U} \left( \frac{t}{T} \right) = \dot{U}_{\text{real}} \left( \frac{t}{T} \right) / U_{\max}$, here $\dot{U}_{\text{real}}$ is the real velocity vector and $U_{\max} = \pi f_0 A_0$ is drag force coefficient and $T$ is the period of hovering motion. However, the above methodology needs to be modified as the effect of deformation
is included in studying hovering motion. In this paper, we adopt the following formula to investigate the work required within T:

\[ P = \int_0^1 \int_I \left( \vec{U}(\frac{t}{T}) \cdot \vec{n}(\frac{t}{T}) \right) p(\frac{t}{T}) d\vec{l}(\frac{t}{T}) \]  

(6)

where \( \bar{U}(t/T) \) is the same dimensionless velocity vector as above; \( \vec{n} \) is the normal unit vector of a moving boundary element surrounding the node; \( p(t/T) \) is dimensionless pressure at the node and \( \vec{l} \) the dimensionless boundary element’s length. In order to study energy consumption in hovering motion for different deformation foil models, we use the Figure-of-Merit \( M \) adopted by Granlund, Ol and Bernal[24], which is the ratio of ideal power to actual power.

\[ M = \frac{C_l^{2/3}}{2P(2A_0/c)^{1/2}} \]  

(7)

All the results obtained by numerical simulations, which includes \( C_l, C_{d}, C_l/C_{d}, \) work, and Figure-of-Merit are plotted in figure 6 and figure 6 shows that both \( C_l \) and \( C_d \) increase with camber amplitude in the full deformation foil model, while the tendency is totally reverse in the partial deformation one. Although work increases with camber amplitude in the full deformation foil model, there exists an optimized value for Figure-of-Merit, 0.3479. The results indicate that larger camber amplitude may not lead to better performance for the full deformation foil model. Among the cases we simulated here, it seems the optimized camber amplitude is 0.1*chord. Compared with the results of fixed chord case (m=0.0), the Figure-of-Merit does not change too much in various chord cases (m>0), for examples, from 0.3278 (m=0.0) to 0.3479 (m=0.1) in full deformation foil model, from 0.3309(m=0.0) to 0.3433(m=0.1) in partial deformation foil model.

(a) Energy consumption profiles for Full deformation foil model

(b) Energy consumption profiles for partial deformation model

Figure 6. Energy consumption profiles for full and partial deformation foil models.

4. Conclusions

In this paper, the effects of deformation on lift force generation mechanisms of wings in hovering flight are investigated. Two foil deformation models, i.e. the full deformation and partial deformation models, are adopted in the research work. The prescribed deformation changes foil morphing during hovering motion in both camber and angle of incidence. The effects of camber amplitude and rotation location on their aerodynamic performances and flow structures are studied in details. The numerical results obtained show that the deformation of foils indeed affects their unsteady aerodynamic
performances during their hovering motion. Foil morphing due to deformation makes both LEV and TEV generation and development processes, as well as the lift force generation mechanisms different from those of the rigid foil model. For the full deformation foil model, the effect of deformation enhances its lift force during both the wake capture and delayed stall. There is an optimized camber amplitude, which is 0.1*chord among those cases simulated.

The results obtained from the partial deformation foil model show that both $C_l$ and $C_d$ decrease with the increase of camber amplitude. The effect of deformation does not enhance lift force due to unfavorable camber in this model, as we discussed in the paper. But TEV is significantly changed by the local AOA due to the deformation of the foil.

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