Research Article

Inflatable Leading Edge-Based Dynamic Stall Control considering Fluid-Structure Interaction

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Received 1 September 2019; Revised 6 December 2019; Accepted 27 December 2019; Published 20 February 2020

Academic Editor: Ennes Sarradj

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The inflatable leading edge (ILE) is explored as a dynamic stall control concept. A fluid-structure interaction (FSI) numerical method for the elastic membrane structure is constructed based on unsteady Reynolds-averaged Navier-Stokes (URANS) and a mass-spring-damper (MSD) structural dynamic model. Radial basis function- (RBF-) based mesh deformation algorithm and Laplacian and optimization-based mesh smoothing algorithm are adopted in flowfield simulations to achieve the pitching oscillation of the airfoil and to ensure the mesh quality. An airfoil is considered at a freestream Mach number of 0.3 and chord-based Reynolds number of 3.92×10^6 . The airfoil is pitched about its quarter-chord axis at a sinusoidal motion. The numerical results indicate that the ILE can change the radius of curvature of the airfoil leading edge, which could reduce the streamwise adverse pressure gradient and suppress the formation of dynamic stall vortex (DSV). Although the maximum lift coefficient of the airfoil is slightly reduced during the control process, the maximum drag and pitching moment coefficients of the airfoil are greatly reduced by up to 66% and 75.2%, respectively. The relative position of the ILE has a significant influence on its control effect. The control laws of inflation and deflation also affect the control ability of the ILE.

1. Introduction

Dynamic stall is a complex aerodynamic problem encountered on helicopter rotors. For a conventional helicopter in forward flight, the angle of attack of the retreating blade is higher than that of the advancing blade, maintaining the torque balance of the airframe. Therefore, the angle of attack of the retreating blade could exceed the static stall angle of attack at a high advance ratio and large thrust coefficient, which results in the occurrence of dynamic stall phenomenon. Dynamic stall refers to a kind of flow phenomenon that the occurrence of stall is delayed beyond the static stall angle of attack, when airfoils are experiencing unsteady motion [1, 2]. During the upstroke motion, a laminar separation bubble (LSB) will appear on the leading edge of the airfoil. With a further increase in the angle of attack, the bursting of the LSB occurs. Following the bursting of the LSB, the DSV emerges [3, 4]. When the DSV moves rapidly toward the trailing edge, the moment stall occurs, which results in excessive blade pitching link loads and limits the flight envelope

of the helicopters [5]. Therefore, many researchers have come up with multiple solutions to this problem.

At present, the main solution used in the industry is to optimize the airfoil shape to improve its dynamic stall characteristics at a relatively low speed. Passive control methods for dynamic stall, such as vortex generator, and disturbance generator, are studied. However, those methods sacrifice other aspects of performance of helicopter rotors in exchange for better dynamic stall characteristics. With the advance of science and technology, researchers begin to investigate active flow control technologies for alleviating or suppressing dynamic stall and hope to obtain a sort of active flow control methods which can be applied in engineering to further improve the helicopter's performance. So far, active flow control methods for dynamic stall have become research hotspots. The widely investigated methods mainly include plasma actuators [6–8], synthetic jet [9, 10], blowing [11–13], dynamically deformable leading edge (DDLE) [14], and trailing edge flap [15–18]. Most of the research on plasma actuators are limited to results obtained under low

FIGURE 1: Schematic of ILE.

FIGURE 2: Wrinkling on the elastic membrane during a pitching cycle.

speed and low Reynolds number conditions. Few studies are aimed at the high speed and high Reynolds number conditions. Further developing the corresponding analytical model for plasma actuators is needed. Blowing-based dynamic stall control could achieve better results under actual flight conditions of helicopter rotors. NASA has carried out a large number of relevant theoretical calculations and wind tunnel experiments and has gained a lot of valuable data [13]. Research on the DDLE is mainly about the numerical simulations and wind tunnel experiments [14, 19, 20]. The existing research is to change the internal structure and mechanism of the blade to realize the deformation. The DDLE could completely change the internal structural arrangement of rotor blades. In addition to this, the blades work in a complex alternating load environment. Hence, it is almost impossible to achieve a DDLE by mechanical

devices. The trailing edge flap-based dynamic stall control for helicopter rotors is the most promising approach in engineering applications. In addition to reducing the pitching moment experienced by the blades during dynamic stall, the trailing edge flap could also be used to reduce the noise from the blade vortex interaction [21]. Recently, Visbal and Benton [22] explored a high-frequency active flow control strategy targeting the natural instabilities of the LSB to delay the formation of DSV, which is worthy of further research.

Xu et al. [23] investigated a dynamic stall control based on the ILE using computational fluid dynamics (CFD) method in two dimensions. The ILE configuration in Ref. [23] refers to a kind of active flow control device that consists of three pieces of elastic membrane connected to the airfoil surface and the relevant inflation and deflation systems. The elastic membrane and the airfoil surface together form

FIGURE 3: Force analysis diagram of the elastic membrane at the deflated state.

FIGURE 4: Mass-spring-damper model.

an inflatable cell and a fairing cell. The inflatable cell can be inflated and deflated by the inflation and deflation systems. The fairing cell is connected to the atmosphere through a pipe to maintain the equilibrium between the internal pressure and the external pressure. The ILE shape was described by a simple geometric method without solving the structural dynamic equation. The results showed that the dynamic stall control method based on the ILE is effective. The influence of the size and relative position of the ILE on the control ability was studied. After completing the work in Ref. [23], the author wrote a fluid-structure interaction numerical method program for the elastic membrane structure in order to study the structural dynamic characteristics of the ILE. During the research, it was found that the “whipping” and “wrinkling” phenomenon appear on the elastic membrane. Then, the ILE configuration in Ref. [23] was modified, and it finally became the ILE device that consists of only a piece of elastic membrane and the relevant inflation and deflation

FIGURE 5: Free body diagram of the elastic membrane node i .

FIGURE 6: Fluid-structure interaction algorithm.

systems. The ILE configuration is investigated using the fluid-structure interaction numerical method in this paper. The flow mechanism of the ILE to suppress the formation of DSV is described in detail. The effect of FSI on the

FIGURE 7: Mesh around the airfoil.

FIGURE 8: Comparison of aerodynamic coefficients between calculation and experiment: (a) lift coefficients, (b) drag coefficients, and (c) pitching moment coefficients.

structural dynamic characteristics of the ILE is discussed. The effect of the elastic modulus and the relative position of the elastic membrane is investigated. Finally, the control laws of the inflation and deflation of the elastic membrane is also studied.

2. ILE Concept and Relevant Illustration

The ILE shapes at inflated and deflated states are shown in Figure 1. The ILE refers to a kind of active flow control device that consists of a piece of elastic membrane connected to the

airfoil surface and the relevant inflation and deflation systems. The elastic membrane and the surface of the airfoil together form a confined space which can be inflated and deflated by the inflation and deflation systems during a pitching cycle. When the airfoil is in the phase of upstroke, the ILE will be inflated and grow in size, changing the shape of the airfoil leading edge. When the airfoil is in the phase of downstroke, the ILE will be deflated and decrease in volume. The elastic membrane attaches fully to the airfoil surface before it moves to the minimum angle of attack.

Dynamic stall occurs near the boundary of the helicopter flight envelope, and it does not occur on the retreating blade at other flight conditions. Hence, it is not necessary to activate the dynamic stall active flow control device under most flight conditions. It is required that the elastic membrane of the ILE can be firmly attached to the airfoil surface under most flight conditions to maintain the original shape of the airfoil. Figure 2 shows the wrinkling phenomenon that may occur in the elastic membrane when the airfoil is in the pitching motion. Wrinkling is prone to occur as the elastic membranes cannot withstand bending loads. Therefore, a reasonable design of the ILE with relevant parameters is required to prevent this phenomenon. Figure 3 displays the force analysis diagram of the elastic membrane at the deflated state. When the ILE is at the deflated state, the prestress on the elastic membrane can be increased through shortening the original length of the elastic membrane AB, so that the resultant force of the tension will be directed to the inside of the airfoil. The original length of the elastic membrane is half of that of curve AB on the airfoil surface in the present work. At the same time, the pressure inside the ILE should be as low as possible at the deflated state. The elastic membrane is pressed against the airfoil surface through the pressure difference between the internal and external of the ILE. Under the combined effect of the tension force and the pressure difference, the wrinkling phenomenon is prevented.

Compared with other active flow control methods for dynamic stall, the ILE can suppress the formation of DSV completely. While maintaining a high lift coefficient, the ILE eliminates the pitching moment load on blades due to DSV. The elastic membranes can be closely attached to the blade surface at the deflated state, maintaining the original high-speed aerodynamic performance of the airfoil. Therefore, the ILE can suppress the formation of DSV on the retreating blade without increasing the drag on the advancing blade. The installation of the ILE does not change the internal structural arrangement of the blades. Of course, there are also some disadvantages for the ILE: for example, (1) it is required that the elastic modulus of the elastic membrane used is sufficiently high to obtain the desired control effect, (2) the wrinkling phenomenon is easy to appear on the elastic membrane, (3) and the elastic membrane is prone to fatigue problems due to the repeated stretching in the inflation and deflation process.

3. Numerical Methodologies

3.1. CFD Numerical Method. The dynamic stall of the rotor airfoil is numerically simulated using the self-programmed

FIGURE 9: Control laws of inflation and deflation during a pitching cycle.

TABLE 1: Details of the control law and structural arrangement parameters.

Case	t_1 (T)	t_2 (T)	f	X_A	X_B
1	0.325	0.75	1.0	11.5%c	1.3%c
2	0.325	0.75	0.95	11.5%c	1.3%c
3	0.325	0.75	0.85	11.5%c	1.3%c
4	0.325	0.75	1.0	10.35%c	1.3%c
5	0.325	0.75	1.0	9.25%c	1.3%c
6	0.325	0.75	1.0	11.5%c	1.9%c
7	0.325	0.75	1.0	11.5%c	2.5%c
8	0.5	0.75	1.0	11.5%c	1.3%c
9	0.75	0.75	1.0	11.5%c	1.3%c
10	0.325	0.5	1.0	11.5%c	1.3%c
11	0.325	0.375	1.0	11.5%c	1.3%c

FIGURE 10: Control laws of inflation and deflation in Case 1.

FIGURE 11: ILE shapes and change in the tension at different angles of attack during a pitching cycle in airfoil frame of reference: (a) upstroke phase and (b) downstroke phase.

FIGURE 12: Comparison of aerodynamic coefficients between the original airfoil and the ILE airfoil in Case 1: (a) lift coefficients, (b) drag coefficients, and (c) pitching moment coefficients.

FIGURE 13: Comparison of aerodynamic coefficients between the original airfoil and the ILE airfoil in Case 1: (a) lift coefficients, (b) drag coefficients, and (c) pitching moment coefficients.

2-D flow solver based on the unstructured hybrid mesh. The finite-volume approach is employed to discretize the governing equations. The convection term is spatially discretized using the AUSM+-up scheme, and the viscous flux is calculated using the Jameson second-order center scheme. In order to simulate the unsteady characteristics of dynamic stall, the dual-time method is used for physical time marching. The pseudotime marching adopts the LU-SGS implicit scheme, which can effectively increase the time step and improve the calculation efficiency. The Spalart-Allmaras turbulence model is employed.

3.2. Mesh Deformation and Smoothing Algorithms. RBF-based mesh deformation algorithm for the unstructured hybrid mesh is employed. Boer et al. [24] firstly applied RBFs to mesh deformation algorithm, which has been widely used due to its strong mesh deformation capability. The basic principle of RBF interpolation-based mesh deformation algorithm is that the displacement of structural boundary nodes is interpolated by RBFs, and then, the boundary displacement effect is smoothly distributed to the whole computational domain by the constructed RBF sequence. There are two main steps in the mesh deformation process.

Firstly, the weight coefficient equation of the object surface node is solved according to the interpolation condition, and then, the computational domain mesh is updated. Although RBF-based mesh deformation algorithm has a strong ability to deal with mesh deformation in a large boundary motion, it generates many poor-quality meshes in some cases. In the present study, a combined Laplacian and optimization-based mesh smoothing algorithm developed by Canann [25] is employed to guarantee the high quality of all meshes.

3.3. Structural Dynamic Model. Modeling of the elastic membrane structure is carried out using the MSD structural dynamic model, which is used widely in the field of parachute research [26]. As shown in Figure 4, the basic principle of the MSD model is to divide the elastic membrane into several mass nodes connected by springs and dampers. In the present work, the damping force terms are ignored. Figure 5 displays the free body diagram of the elastic membrane node i . T_1 is the tension between node i and node $i-1$, and T_2 is the tension between node i and node $i+1$. For the sake of simplicity, suppose that the elastic membrane material obeys Hooke's law which reads that tension is linear with strain.

Hence, T_1 increases linearly with the strain, and T_2 is treated in the same way. F_1 is the pressure force due to pressure difference on the membrane from node $i - 1$ to node i . F_2 is the pressure force due to pressure difference on the elastic membrane from node i to node $i + 1$. F_3 is the contact force between the elastic membrane and the airfoil surface.

In this section, the equations of motion for the elastic membrane nodes are described. The acceleration in the x direction of the elastic membrane node i is given as

$$m_i \frac{d^2 x_i}{dt^2} = T_{1i} \cdot \cos \alpha_{1i} + T_{2i} \cdot \cos \alpha_{2i} + F_{1i} \cdot \cos \left(\alpha_{1i} - \frac{\pi}{2} \right) + F_{2i} \cdot \cos \left(\alpha_{2i} + \frac{\pi}{2} \right) + F_{3i} \cdot \cos \alpha_{3i}. \quad (1)$$

The acceleration in the y direction of the elastic membrane node i is given as

$$m_i \frac{d^2 y_i}{dt^2} = T_{1i} \cdot \sin \alpha_{1i} + T_{2i} \cdot \sin \alpha_{2i} + F_{1i} \cdot \sin \left(\alpha_{1i} - \frac{\pi}{2} \right) + F_{2i} \cdot \sin \left(\alpha_{2i} + \frac{\pi}{2} \right) + F_{3i} \cdot \sin \alpha_{3i}. \quad (2)$$

The matrix form of Equations (1) and (2) can be written as

$$M \cdot \ddot{\xi} = F. \quad (3)$$

It is the simplified form of aeroelastic equation of a two-dimensional airfoil [27]. Considering the damping, we have

$$M \cdot \ddot{\xi} + G \cdot \dot{\xi} + K \cdot \xi = F, \quad (4)$$

where M is the mass matrix, and G is the damping matrix, and K is the stiffness matrix, and F is the generalized force vector. The equation is the dynamic equation of all nodes on the elastic membrane.

3.4. Contact and Impact Algorithm. During the airfoil pitching oscillation, the inflation and deflation of ILE will cause the elastic membrane to contact the airfoil surface, which requires the contact and impact algorithm to analyze. The contact and impact algorithm based on the penalty function [28] is employed in the present work. The basic principle of the algorithm is to check whether each slave node penetrates the main surface at each time step, and if there is no penetration, no treatment is needed. The contact force calculation formula is written as

$$F_3 = \begin{cases} kd_{n+1} & d_{n+1} > d_n \\ 0 & d_{n+1} \leq d_n \end{cases}, \quad (5)$$

where F_3 is the contact force between the elastic membrane and the airfoil surface, and k is the set elastic modulus,

FIGURE 14: Streamlines and pressure coefficient contours of the original airfoil and the ILE airfoil in Case 1 at different angles of attack.

FIGURE 15: Pressure distributions on the airfoil surface at different angles of attack.

FIGURE 16: Streamlines and Mach number contours near the leading edge in airfoil frame of reference at different angles of attack.

and d is the penetration depth. If penetrated, a large interfacial contact force is introduced between the slave node and the main surface penetrated, the magnitude of which is proportional to the penetration depth. In order to prevent the nonphysical bounce phenomenon in the contact between the elastic membrane and the surface of the airfoil, a judgment condition is added to the calculation process of the contact force. That is, if the penetration distance at time $n+1$ is equal to or less than that at time n , then the contact force at time $n+1$ is zero. In the present work, only the normal contact force is calculated, and the tangential friction is ignored. The thickness of the elastic membrane is ignored in the contact and impact process.

3.5. RBF-Based Data Transfer Algorithm between Fluid and Structure Domains. In general, the mesh density of the fluid domain is much bigger than that of the structure domain, which results in that the meshes in different domains do not match at their common interface. It is a difficult task to transfer data between two nonmatching meshes in a reasonable way, and this is the interpolation problem in FSI analysis. Although many approaches are developed for the problem, a common disadvantage of these approaches is that the data transfer often depends on the connectivity relationship between the two meshes.

In the present work, the RBF-based interpolation algorithm [29] is employed to deal with the data transfer between fluid and structure domains. An outstanding

FIGURE 17: Skin friction coefficient distributions on the airfoil upper surface at different angles of attack.

FIGURE 18: Contours of vorticity magnitude of the original airfoil and the ILE airfoil in Case 1 at different angles of attack.

advantage of this algorithm is that the need to specify any connectivity information is removed entirely. It is easy to transfer data between the two meshes, even for poor-quality meshes where the fluid and structure domains may cross each other.

3.6. Loosely Coupled Fluid-Structure Interaction Algorithm. The fluid-structure interaction algorithm used in the present

work is loosely coupled. Figure 6 shows the flowchart of the fluid-structure interaction algorithm. In the loosely coupled algorithm, it is convenient to use the existing CFD code and CSD code to realize the numerical simulation of fluid-structure interaction. Equation (4) is solved by the hybrid linear multistep method [27].

Defining the elastic membrane structural state-vector as $E = [\xi_1, \xi_2, \dots, \xi_N, \dot{\xi}_1, \dot{\xi}_2, \dots, \dot{\xi}_N]^T$, the dynamic

FIGURE 19: Comparison of aerodynamic coefficients between different cases: (a) lift coefficients, (b) drag coefficients, and (c) pitching moment coefficients.

Equation (4) in the state space can be written as follows:

$$\dot{E} = f(E, t) = A \cdot E + B \cdot F(E, t), \quad (6)$$

where

$$A = \begin{pmatrix} 0 & I \\ -M^{-1}K & -M^{-1}G \end{pmatrix}, \quad (7)$$

$$B = \begin{pmatrix} 0 \\ M^{-1} \end{pmatrix}.$$

Equation (6) can be integrated by the standard second-order explicit Adams linear multistep scheme.

$$\begin{aligned} E_{n+1} &= E_n + \frac{\Delta t}{2} (3f_n - f_{n-1}) \\ &= E_n + \frac{\Delta t}{2} (3A \cdot E_n - A \cdot E_{n-1}) + \frac{\Delta t}{2} (3B \cdot F_n - B \cdot F_{n-1}). \end{aligned} \quad (8)$$

It can also be integrated by the second-order implicit Adams linear multistep scheme based on the predictor-corrector procedure.

$$\begin{cases} \bar{E}_{n+1} = E_n + \frac{\Delta t}{2} (3f_n - f_{n-1}) = E_n + \frac{\Delta t}{2} (3A \cdot E_n - A \cdot E_{n-1}) + \frac{\Delta t}{2} (3B \cdot F_n - B \cdot F_{n-1}), \\ E_{n+1} = E_n + \frac{\Delta t}{2} [f_n + f_{n+1}(\bar{E}_{n+1}, t + \Delta t)] = E_n + \frac{\Delta t}{2} (A \cdot E_n + A \cdot \bar{E}_{n+1}) + \frac{\Delta t}{2} [B \cdot F_n + B \cdot F_{n+1}(\bar{E}_{n+1}, t + \Delta t)]. \end{cases} \quad (9)$$

FIGURE 20: The ILE shapes and pressure coefficient distributions at different angles of attack for Cases 1, 2, and 3.

For the corrector step of Equation (9), F_{n+1} is extrapolated by Equation (10).

$$F_{n+1} = 2F_n - F_{n-1} \quad (10)$$

Substituting Equation (10) into Equations in (9), the second-order hybrid linear multistep scheme is obtained.

$$\begin{cases} \bar{E}_{n+1} = E_n + \frac{\Delta t}{2}(3f_n - f_{n-1}) = E_n + \frac{\Delta t}{2}(3A \cdot E_n - A \cdot E_{n-1}) + \frac{\Delta t}{2}(3B \cdot F_n - B \cdot F_{n-1}), \\ E_{n+1} = E_n + \frac{\Delta t}{2}[f_n + f_{n+1}(\bar{E}_{n+1}, t + \Delta t)] = E_n + \frac{\Delta t}{2}(A \cdot E_n + A \cdot \bar{E}_{n+1}) + \frac{\Delta t}{2}[3B \cdot F_n + B \cdot F_{n-1}]. \end{cases} \quad (11)$$

4. Pitching Oscillation and Relevant Parameters

The airfoils are considered at a freestream Mach number of 0.3 and chord-based Reynolds number of 3.92×10^6 . The airfoils are pitched about the quarter-chord axis according to the following expression:

$$\alpha(t) = \alpha_0 + \alpha_m \cdot \sin\left(\omega t - \frac{\pi}{2}\right), \quad (12)$$

where α_0 and α_m are the mean angle of 9.78 deg and the pitch oscillation amplitude of 9.90 deg, respectively [30].

FIGURE 21: Comparison of aerodynamic coefficients between different cases.

For airfoils in pitching oscillation, the reduced frequency κ is usually used to describe the unsteady motion, which is defined as

$$\kappa = \frac{\omega c}{2V_{\infty}}, \quad (13)$$

where c is the chord length, and V_{∞} is the velocity of the free-stream. The airfoil chord length is 0.61 m. The reduced frequency $\kappa = 0.099$ is employed.

The purpose of adding the $-\pi/2$ term in the expression is to make sure that the angle of attack is the minimum at the initial moment, which is very important for the FSI analysis.

Because the pitching rate is zero at the minimum angle of attack, it can be guaranteed that the initial velocity and acceleration of the structural nodes are both zero.

5. Results and Discussions

5.1. Verification of Numerical Method. The reliability of the numerical method is verified by calculating the unsteady aerodynamic force of the original airfoil under the dynamic stall condition. The original airfoil is SC1095. To assess the effect of mesh resolution, three meshes of different sizes are generated. For all the meshes, the first layer spacing is equal to $10^{-5}c$ to ensure that the y^+ is less than 1. Figure 7 shows the mesh around the airfoil. The far-field boundary is located more than 100 times chord length away from the airfoil. The total number of mesh cells is increased from 23 thousand for the coarse mesh to 130 thousand for the fine mesh. A pitching cycle is equally divided into 2000 physical time steps in order to accurately simulate the unsteady aerodynamic characteristics of the airfoils during the pitching oscillation. The subiteration convergence criterion is that the nondimensional residual value is reduced to 1.0×10^{-5} . The results of three different meshes are shown in Figure 8. As shown in the figure, the numerical results of all the meshes agree fairly well with the experimental data. It is proved that the numerical method can be employed to simulate the unsteady aerodynamic characteristics of the airfoils under the dynamic stall condition. Unless otherwise noted, the fine mesh is employed to investigate the aerodynamic characteristics of the airfoils.

5.2. Details of the Control Laws of Inflation and Deflation and Simulation Cases. The control laws of inflation and deflation during a pitching cycle are shown in Figure 9. t denotes the duration time of a pitching cycle. During a pitching cycle, the airfoil starts to rise, and the ILE is inflated simultaneously. At the start, pressure in the ILE is the lowest pressure of 0.5 atm. When t reaches t_1 , the pressure reaches the maximum of 4 atm. The airfoil continues the pitching motion. When t reaches t_2 , the ILE begins to deflate. During the deflation process, pressure in the ILE decreases linearly. When the airfoil is pitched to the minimum angle of attack, the pressure reaches the minimum of 0.5 atm.

Table 1 shows the relevant parameters of the control law and structural arrangement in different cases. f indicates the ratio of the elasticity modulus of the elastic membrane material in each case to that in Case 1, which is employed to investigate the effect of the elasticity modulus on the dynamic stall control. X_A represents the position of point A. In the same way, X_B represents the position of point B relative to the airfoil chord.

5.3. ILE Shape Change in the Inflation and Deflation Process. Before investigating the effect of ILE on dynamic stall, it is necessary to discuss how the ILE shape changes during the pitching oscillation at a freestream velocity of zero. Figure 10 shows the control laws of inflation and deflation during a pitching cycle in Case 1. The shapes and ratios of the tension of the ILE at different angles of attack during a pitching cycle in Case 1 are shown in Figure 11. R represents the ratio of the

FIGURE 22: ILE shapes at an angle of attack of 19.26 deg downstroke in airfoil frame of reference.

tension on the elastic membrane at different angles of attack to that at the minimum angle of attack.

The pitching rate of the airfoil is zero at the minimum angle of attack, i.e., t is equal to 0.0T. As shown in Figure 11(a), the elastic membrane of the ILE tightly attaches to the surface of the airfoil due to the pressure difference and its own tension, and the tension distribution on the elastic membrane is uniform. During the upstroke process, the ILE becomes bigger and bigger due to pressure difference, which results in higher tension on the elastic membrane. When the angle of attack is 14.27 deg, i.e., t is equal to t_1 , pressure in the ILE is the maximum. The tension on the elastic membrane approaches the maximum. The ILE shape almost remains the same in the process from 14.27 deg upstroke to 9.78 deg downstroke, which is attributed to the constant pressure in the ILE and the sufficiently high elasticity modulus of the elastic membrane material. The sufficiently high elasticity modulus can effectively reduce the effect of the pitching motion on the ILE shape.

As shown in Figure 11(b), as the airfoil continues to pitch down, the ILE begins to shrink rapidly under the action of its own tension and the pressure difference between the inside and outside of it. When the airfoil reaches the minimum angle of attack, the elastic membrane of ILE completely attaches to the surface of the airfoil. Although the elastic membrane attaches to the surface of the airfoil at 1.0T, the tension distribution is nonuniform, which will affect the ILE shape during the next pitching cycle. Therefore, the initial position and zero are reassigned to the coordinates and velocity of all the nodes at the minimum angle of attack, respectively. The purpose of this is to avoid the effect of the nonuniform distribution of the tension on the ILE shape.

5.4. The Effect of ILE on Static Stall. Before studying the effect of ILE on dynamic stall, it is necessary to study its effect on the airfoil static stall. Figure 12 shows a comparison of the aerodynamic coefficients between the original airfoil and the ILE airfoil in Case 1.

FIGURE 23: Pressure coefficient distributions at an angle of attack of 19.26° downstroke.

FIGURE 24: Comparison of aerodynamic coefficients for Cases 1, 4, and 5: (a) lift coefficients, (b) drag coefficients, and (c) pitching moment coefficients.

FIGURE 25: Comparison of ILE shapes at angles of attack of 17.69 and 19.32 deg upstroke for Cases 1, 4, and 5.

FIGURE 26: Comparison of pressure coefficient distributions at angles of attack of 17.69 and 19.32 deg upstroke for Cases 1, 4, and 5.

The freestream Mach number is 0.3. As shown in the figure, the stall angle of attack of the ILE airfoil is increased by 2.95 deg. At the same time, the maximum lift coefficient is increased by 0.268. It is proved that the ILE can delay the occurrence of static stall. At a low angle of attack, the drag of the ILE airfoil is higher than that of the original airfoil. The pitching moment coefficient of the ILE airfoil firstly increases as the angle of attack increases when the airfoil angle of attack is less than 13.0 deg. Then, the pitching moment coefficient of the ILE airfoil decreases as the angle of attack increases. When the angle of attack is higher than

the static stall angle of attack, the ILE airfoil pitching moment coefficient increases dramatically.

5.5. The Effect of ILE on Dynamic Stall and Analysis of Control Mechanism. From comparisons of the aerodynamic coefficients (shown in Figure 13), it is fairly apparent that ILE is able to delay the lift stall and to reduce the peak of drag and pitching moment coefficients in Case 1. The maximum lift coefficient of the ILE airfoil is reduced by almost 8.2% compared with the maximum lift coefficient of the original airfoil. Although the maximum lift coefficient of the ILE

FIGURE 27: Streamlines and Mach number contours in Case 5 at different angles of attack.

airfoil is slightly reduced, the maximum drag and pitching moment coefficients of the ILE airfoil are greatly reduced by up to 50.1% and 55.3%, respectively, compared with that of the original airfoil.

A description of the flowfield evolution for the pitching airfoils is provided. Figure 14 shows the flowfield streamlines and pressure coefficient contours of the original airfoil and the ILE airfoil in Case 1 at different angles of attack. Figure 15 displays the pressure distributions on the airfoil surface at different angles of attack.

For the original and ILE airfoils, the flow is attached at an angle of attack of 13.30 deg, and the C_p peak is lower than -10 in Figure 15(a). The C_p peak of the original airfoil exceeds -11, which results in the formation of the LSB in the vicinity of the airfoil leading edge (shown in Figure 16(a), a1). As shown in Figure 17(a), the skin friction coefficients at a part of the upper surface of the original airfoil are negative values at an angle of attack of 14.43 deg due to the appearance of LSB. Figures 16(b), b1 and 17(a) display that the LSB does not exist in the vicinity of the ILE airfoil leading edge. The skin friction coefficient is positive. With a further increase in the angle of attack, the LSB becomes bigger and moves towards the trailing edge. The bursting of the LSB occurs due to the increasing adverse pressure gradient. Following the bursting of the LSB, the DSV emerges on the original airfoil (shown in Figure 16).

From 14.43 deg to 16.89 deg, the DSV on the original airfoil begins to move toward the trailing edge and grows in size,

which results in a rapid increase of the pitching moment coefficient of the original airfoil. The moment stall occurs, as shown in Figure 13(c). A low pressure area is formed on the upper surface of the original airfoil at an angle of attack of 16.89 deg. Figure 17(b) shows that the skin friction coefficients at a part of the upper surface of the original airfoil at an angle of attack of 16.89 deg are negative values due to the appearance of DSV. As the angle of attack increases from 16.89 deg to 17.97 deg, the lift slope augments and the lift coefficient increases rapidly, as shown in Figure 13(a). The vorticity contour of the original airfoil is shown in Figure 18(a), a2, and the vorticity contour of the ILE airfoil is shown in Figure 18(b), b2.

As shown in Figure 13(a), the lift coefficient reaches the maximum at an angle of attack of 17.97 deg. As the DSV continues to move towards the trailing edge, the lift stall occurs, and the lift coefficient decreases sharply. When the angle of attack reaches the maximum of 19.68 deg, the original airfoil is at fully stall condition. When the original airfoil is down to the angle of attack of 8.22 deg, the flow on the airfoil surface is restored to the attached state.

The DSV is completely suppressed for the ILE airfoil. Peaks of drag and pitching moment coefficients on the ILE airfoil are greatly reduced. The reason why the DSV is completely suppressed is that the ILE alters the curvature distribution of the leading edge, which effectively reduces the streamwise adverse pressure gradient on the ILE airfoil surface. Therefore, the formation of DSV is suppressed during

FIGURE 28: Comparison of aerodynamic coefficients for Cases 1, 6, and 7: (a) lift coefficients, (b) drag coefficients, and (c) pitching moment coefficients.

the pitching oscillation. From Figure 13(c), it is noticed that the peak of the pitching moment coefficient due to DSV is greatly reduced.

5.6. The Effect of the Elasticity Modulus. The mechanism of controlling dynamic stall using ILE is discussed above. The numerical results in Case 1 indicate that the ILE suppresses the formation and development of DSV, reducing the peak of drag and pitching moment coefficients. In this section, the effect of the elasticity modulus on dynamic stall control is discussed.

The elasticity modulus of the elastic membrane in Cases 1, 2, and 3 is reduced in turn, as shown in Table 1. Figure 19 shows that peaks of pitching moment coefficient in these three cases are different. The maximum lift coefficient of the ILE airfoil in Case 3 is reduced by almost 8.1% compared with that of the original airfoil. Although the maximum lift coefficient of the ILE airfoil is slightly decreased during a pitching cycle in Case 3, the maximum drag and pitching moment coefficients of the ILE airfoil are greatly reduced by up to 66% and 75.2%, respectively, compared with that of the original airfoil. The numerical results show

that with decreasing elastic modulus, the maximum drag and pitching moment coefficients of the ILE airfoils decrease and the maximum lift coefficients slightly increases. The higher the elasticity modulus of the elastic membrane is, the bigger the peak of drag and pitching moment coefficients are. In other words, as the elasticity modulus of the elastic membrane increases, the dynamic stall control ability of the ILE declines.

After analyzing the ILE shapes and the flowfield data during a pitching cycle in these three cases, it is shown that a lower elasticity modulus results in a larger ILE shape at the same pressure in the ILE, which makes the effective chord length of the airfoil longer and increases the force area. Figure 20 displays the ILE shapes and the pressure distributions at angles of attack of 17.97 deg upstroke and 19.26 deg downstroke in Cases 1, 2, and 3. The ILE shape in Case 3 is larger than that in Case 1. The shape change of the ILE also changes the pressure distributions on the airfoil surface in these three cases. The larger ILE changes the pressure distribution on the airfoil surface and moves the center of pressure toward the leading edge of the airfoil, which results in a lower pitching moment coefficient than that in Case 1.

FIGURE 29: Comparison of the ILE shapes at angles of attack of 18.92 deg upstroke and 19.68 deg in airfoil frame of reference for Cases 1, 6, and 7.

FIGURE 30: Comparison of ILE shapes at different angles of attack upstroke in airfoil frame of reference for Case 7.

5.7. The Effect of FSI. The ILE is a kind of flexible membrane structure undergoing a periodic deformation during the pitching oscillation. Hence, it is necessary to investigate the effect of FSI on the dynamic stall of the ILE airfoils. In this section, the effect of FSI on dynamic stall control is discussed. The elasticity modulus of the elastic membrane in Cases 1 and 3 is reduced in turn, as shown in Table 1.

As shown in Figure 21, for Cases 1 and 3, the peak of pitching moment coefficients considering FSI is inconsistent with that of non-FSI. Non-FSI denotes that the effect of FSI is ignored and the pressure outside the ILE is assumed to 1 atm during the pitching oscillation. As shown in Figures 21(a), a2, and 21(b), b2, a difference value in the peak of drag coefficients between FSI and non-FSI for Case 3 is bigger than that for Case 1. As shown in Figures 21(a), a3, and 21(b), b3, the difference of the peak of pitching moment coefficients

between FSI and non-FSI for Case 3 is bigger than that for Case 1. From the comparison of the drag and pitching moment coefficients, the effect of FSI becomes stronger as the elasticity modulus of the elastic membrane decreases. Since a higher elasticity modulus of the elastic membrane has a stronger ability to reduce the role of the freestream dynamic pressure, the smaller the elasticity modulus is, the stronger is the effect of FSI on the pitching moment coefficients. Figure 22 shows the ILE shapes from Case 1 to Case 3 at an angle of attack of 19.26 deg downstroke, where the solid line represents FSI, and the dotted line represents non-FSI. Figure 23 shows the pressure coefficient distributions at an angle of attack of 19.26 deg downstroke. Due to the low pressure area near the leading edge of the airfoil, the portion of the elastic membrane close to point B bulges, comparison with non-FSI in these cases. Therefore, materials

FIGURE 31: Streamlines and Mach number contours in Case 7 at different angles of attack.

with high elasticity modulus should be used as much as possible in order to reduce the effect of freestream on the ILE shape.

5.8. The Effect of the Position of Point A. The position of point A in Cases 1, 4, and 5 gradually moved toward the leading edge of the airfoil, as shown in Table 1. The position of point A relative to the airfoil chord in Cases 1, 4, and 5 are 11.5%, 10.35%, and 9.25%, respectively.

Figure 24 displays the aerodynamic coefficients in Cases 1, 4, and 5. The numerical results indicate that the occurrence of dynamic stall in these three cases is delayed due to the role of the ILE. The position of point A is too close to the leading edge, and the control ability of the ILE for dynamic stall is reduced. The ILE loses the ability to suppress the formation of DSV in Case 5, which results in a sharp increase in the peak of pitching moment coefficient. The peak of pitch-

ing moment coefficient in Case 5 is bigger than that of the original airfoil.

The cause of this phenomenon is that the “too small” ILE cannot suppress the formation of DSV in Case 5. Figure 25 shows the ILE shapes at angles of attack of 17.69 deg and 19.32 deg upstroke for Cases 1, 4, and 5. Obviously, the closer the point A is to the leading edge, the smaller the ILE shape is. The forward movement of the position of point A causes the elastic membrane AB to become shorter. When resisting the same pressure difference, the shorter elastic membrane requires less deformation, which results in the ILE shape in Case 5 is smaller than that in Case 1. Therefore, the radius of curvature of the airfoil leading edge in Case 5 is smaller than that in Case 1. As shown in Figures 26(a) and 26(b), the “too small” radius of curvature at the airfoil leading edge in Case 5 causes a higher adverse pressure gradient and results in the formation and development of DSV. Figure 27 displays

FIGURE 32: Control laws of inflation and deflation for Cases 1, 8, and 9.

FIGURE 33: Comparison of aerodynamic coefficients for Cases 1, 8, and 9: (a) lift coefficients, (b) drag coefficients, and (c) pitching moment coefficients.

FIGURE 34: Comparison of ILE shapes at different angles of attack upstroke in airfoil frame of reference.

the formation and development of DSV in Case 5 at different angles of attack.

5.9. The Effect of the Position of Point B. The position of point B in Cases 1, 6, and 7 gradually moved toward the trailing edge of the airfoil, as shown in Table 1. The position of point B relative to the airfoil chord in Cases 1, 6, and 7 are 1.3%, 1.9%, and 2.5%, respectively.

Figure 28 shows the aerodynamic coefficients of Cases 1, 6, and 7. The numerical results indicate that the occurrence of dynamic stall in the three cases is delayed due to the effect of ILE. But the ILE loses the ability to suppress the formation of DSV in Cases 6 and 7, which results in a sharp increase in the maximum pitching moment coefficient of the airfoil.

The reason why ILE loses its ability to suppress the formation of DSV is that the elastic membrane close to point B forms a “pit” during the pitch-up motion, and the pit results in the formation of DSV in Cases 6 and 7. Figures 29(a) and 30(a) display the position of the pit. The elastic membrane near point B bulges in Cases 6 and 7, forming a pit with the airfoil surface. Because point B in Cases 6 and 7 moves toward the trailing edge of the airfoil, the length of the elastic membrane becomes longer. The ILE is required to be larger than that of Case 1 to produce a high enough tension to balance the pressure difference between the lead-

ing edge suction and pressure in the ILE. As shown in Figure 29(a), the more point B moves toward the trailing edge, the more the elastic membrane bulges. When the maximum angle of attack of 19.68 deg is reached, the leading edge suction collapses. Pressure difference between the inside and outside of the ILE becomes smaller. As a result, the pit becomes smaller than that at an angle of attack of 18.92 deg. Figure 30 shows the ILE shapes at different angles of attack in Case 7, and Figure 31 shows the streamline and Mach number contours at corresponding angles of attack in Case 7. When the angle of attack is at 18.11 deg, a separation vortex is formed in the pit. The separation vortex becomes stronger when the angle of attack reaches 18.61 deg. With the further increase of the angle of attack, the separation vortex breaks down and dynamic stall occurs.

5.10. The Effect of t_1 . The values of t_1 in Cases 1, 8, and 9 are gradually increased, as shown in Table 1. The values of t_1 in Cases 1, 8, and 9 are 0.325 T, 0.5 T, and 0.75 T, respectively. The control laws of inflation and deflation in Cases 1, 8, and 9 are shown in Figure 32.

Figure 33 displays the aerodynamic coefficients in Cases 1, 8, and 9. Although the occurrence of dynamic stall is delayed in these three cases, the ILE does not prevent the formation and development of DSV in Cases 8 and 9, which

FIGURE 35: Streamlines and Mach number contours of the ILE airfoil in Case 8 at different angles of attack upstroke.

results in a sharp increase in the maximum pitching moment coefficient of the airfoil.

The reason why the ILE loses the ability to control dynamic stall in Cases 8 and 9 is that the ILE is “too small”. Figure 34 shows a comparison of ILE shapes at different angles of attack upstroke in Cases 8 and 9. Figure 35 displays the formation and development of DSV in Case 8. When the angle of attack reaches 16.89 deg, the ILE shape in Case 8 is too small to prevent the formation of LSB (shown in Figure 35(a)). The “too small” ILE does not sufficiently reduce the streamwise adverse pressure gradient on the airfoil surface and ultimately leads to the formation and development of LSB. With the further increase of the angle of attack, the LSB breaks down, and dynamic stall occurs.

5.11. The Effect of t_2 . As shown in Table 1, the values of t_2 in Cases 1, 10, and 11 are gradually reduced to study the effect of t_2 on the dynamic stall control during a pitching cycle. The values of t_2 in Cases 1, 10, and 11 are 0.75 T, 0.5 T, and 0.375 T, respectively. Figure 36 shows the control laws of inflation and deflation in Cases 1, 10, and 11.

Figure 37 displays the aerodynamic coefficients in Cases 1, 10, and 11. Figure 38 shows a comparison of ILE shapes and pressure coefficient distributions at different angles of attack for Cases 1, 10, and 11. The numerical results indicate

FIGURE 36: Control laws of inflation and deflation for Cases 1, 10, and 11.

that the ILE loses the ability to control dynamic stall in Case 11. From the above described, if the value of t_1 is “too big”, the ILE will lose the ability to control dynamic stall. Conversely, if the value of t_2 is “too small”, the ILE will lose the ability to control dynamic stall. The DSV will emerge. The

FIGURE 37: Comparison of aerodynamic coefficients for Cases 1, 10, and 11: (a) lift coefficients, (b) drag coefficients, and (c) pitching moment coefficients.

value of t_2 is equal to $0.375 T$ in Case 11 means that the ILE performs the deflation operation before the maximum angle of attack. Due to deflation before the maximum angle of attack, the smaller ILE shape increases the streamwise adverse pressure gradient, and the LSB emerges, as shown in Figures 38(a), a2, and 38(b), b2. With the further increase of the angle of attack, the LSB breaks down, and the DSV emerges. The DSV leads to a higher peak of pitching moment coefficient of the ILE airfoil in Case 11 compared with that of the original airfoil.

6. Conclusions

The ILE-based dynamic stall control is numerically studied, using the FSI numerical method for the elastic membrane structure. The original airfoil and ILE airfoils are considered at a freestream Mach number of 0.3 and chord-based Reynolds numbers of 3.92×10^6 . The airfoils are pitched about their quarter-chord axis at a sinusoidal oscillation. Dynamic stall control based on ILE is studied in detail. This paper mainly focuses on the ILE shape variation and

the mechanism of controlling dynamic stall during the pitching oscillation.

The numerical results show that the ILE is able to change the shape of the airfoil leading edge. The larger leading edge of the airfoil makes the radius of curvature bigger. Under the control laws of inflation and deflation, the ILE increases the radius of curvature at the maximum angle of attack and fully attaches to the airfoil surface at the minimum angle of attack. The analysis of the flowfield data indicates that the ILE is capable of decreasing the streamwise adverse pressure gradient in the vicinity of the airfoil leading edge and suppressing the formation of DSV under appropriate structural parameters and control laws. However, the ILE loses its ability to control dynamic stall in some cases. The movement of point A (a joint point of the elastic membrane to the airfoil surface) toward the leading edge results in a relatively small ILE shape at the maximum angle of attack, which reduces the ability to suppress the DSV. The movement of point B (a joint point of the elastic membrane to the airfoil surface) toward the trailing edge results in a pit that leads to a separation vortex and causes the occurrence of dynamic stall. Both “too big” value of t_1 (the moment that the pressure in the ILE reaches

FIGURE 38: Comparison of ILE shapes and pressure coefficient distributions at different angles of attack for Cases 1, 10, and 11.

the maximum during the inflation process) and “too small” value of t_2 (the moment that the pressure in the ILE starts to decline) could also be the cause that the ILE loses the ability to suppress the formation of DSV.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was partially supported by the National Natural Science Foundation of China (Grant nos. 11972306, 11472223), the Fundamental Research Funds for the Central Universities of China (Grant no. 310201901A004), the Foundation of National Key Laboratory, and the 111 Project of China (B17037). The authors would like to acknowledge the computing services from the High Performance Computing Center of Northwestern Polytechnical University.

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