Unsteady numerical simulation of flap vibration for 30P30N three-element airfoil

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Abstract. The pitching motion of NACA0012 airfoil and the flap vibration of 30P30N multi-element airfoil are simulated by using commercial fluid dynamics simulation software Fluent. The influence of flap vibration on lift coefficient and pitch moment coefficient of multi-element airfoil is analyzed. The results show that the influence of flap vibration on pitching moment coefficient of multi-element airfoil is greater. With the increase of flap amplitude, the variation range of lift and moment coefficients gradually increases, while with the increase of frequency, the variation range of lift and moment coefficients gradually decreases, and the hysteresis loop gradually becomes "thin" and its shape tends to ellipse. With the increase of flap vibration frequency, the unsteady effect of flow field increases, and the hysteresis loop may change in reverse direction.

Keywords: unsteady; numerical simulation; multi-element airfoil; flap; vibration

1. Introduction

Aircraft are all elastomers, which will produce structural deformation under the action of aerodynamic force, and structural deformation will cause additional aerodynamic force, and this additional aerodynamic force will cause additional deformation of the structure, which is aeroelasticity [1]. Aerodynamic elasticity has a significant impact on the maneuverability and stability of aircraft, which may cause structural damage or flight accidents. Therefore, aeroelasticity is an important issue to be considered in aircraft design.

In the take-off and landing phase of an aircraft, it is necessary for the augmenter to provide a larger lift coefficient to ensure that the aircraft has sufficient lift [2]. The research of lifting device is an important part of the design of high lift system. When the lifting device is opened, the wing changes from compact structure to decentralized structure, and its stiffness will decrease. Because of the low speed pressure, the aeroelastic problem of the wing will not occur, so the aeroelastic problem of the lift device is mainly static aeroelastic research.

However, although the whole wing will not have aerodynamic problems, there are local vibration. Figure. 1 is an elevator for a typical passenger aircraft. The red frame covers the trailing edge flap. It is
observed that when the aircraft is in the take-off and landing stage (especially the landing stage), the flap will vibrate, and the farther away from the guide rail, the greater the vibration. Flap vibration will inevitably affect the lift, noise and structure of aircraft.

![Figure 1. High lift system of typical civil aircraft.](image1)

![Figure 2. Flap vibration direction.](image2)

There are few studies on unsteady aerodynamic forces caused by flap vibration. Liu [3] simulated the simple harmonic oscillation of the flap around a quarter of their chord points, and gave the variation of aerodynamic coefficients with the movement of the flap. Zhang [4] assumes that the flap oscillate around 10% chord points, and obtains the variation of lift coefficients of each component with the flap deflection angle. These studies assume that the flap pitch around an axis, but in fact the flap basically sink and float along the normal direction of the guide plane, as shown in Figure 2. In the figure, the flap are fixed by two guide rails. The stiffness of the guide rails is very large, while the stiffness of the flap themselves is relatively small. After the lifting device is opened, the flap are equivalent to two fixed cantilever beams, so the deformation of the flap is mainly bending, in-plane deformation and torsion deformation can be neglected, so the floating and sinking motion of points A, B and C along the direction of the blue arrow is the most obvious. The movement of the flap will cause the variation of the parameters of the seam, thus changing the aerodynamic characteristics of the lift device.

This paper assumes that the flap oscillate in the normal direction along the chord of the flap, and calculates the influence of the flap motion amplitude and frequency on the lift coefficient and pitch moment coefficient of the multi-element airfoil.

2. Numerical model

2.1. Mesh

The grid is a structured/unstructured hybrid grid, as shown in Figure 3. In order to minimize the computational error caused by mesh deformation in unsteady calculation, the boundary layer mesh around the flap moves with the flap. The red mesh is the mesh of the deformed area. The flap oscillate harmonically along the blue arrow in the figure, and the angle between the moving direction and the horizontal direction is 60 degrees.

![Figure 3. Hybrid mesh of 30P30N multi-element airfoil.](image3)
2.2. Verification

The commercial fluid dynamics simulation software Fluent is used as a solver to solve the flow field, and the moving grid method is a linear elastic entity smoothing method. Figure 4 shows the lift coefficient hysteresis loop of NACA0012 airfoil compared with experimental result [5]. The calculation conditions are $Ma=0.755$, $Re=5.5 \times 10^6$, the angle of attack varies as follows

$$\alpha = 0.016^\circ + 2.51^\circ \sin(\alpha t)$$  \hspace{1cm} (1)

$$\omega = \frac{2kV}{L}$$ \hspace{1cm} (2)

Where $k$ is the reduction frequency set as 0.0814, $V$ and $L$ represent the reference speed and the reference chord length respectively. Figure 5 is the steady pressure coefficient distribution of 30P30N multi-element airfoil compared with wind tunnel experiment [6]. The calculation conditions are: $U_\infty=58$ m/s, $Re=1.71 \times 10^6$, and $\alpha=5.5^\circ$. Both steady and unsteady simulation results are in good agreement with the experimental values.

3. Results and discussion

Assume that the displacement of the flap is

$$\delta = A \cdot \sin(2\pi ft)$$ \hspace{1cm} (3)

Where $A=0.001C$, $0.002C$, $0.003C$, $f=5$ Hz, $10$ Hz, $15$ Hz, $C$ is the original airfoil length. The positive displacement indicates that the flap move upward and the slots narrow, while the negative displacement indicates that the flap move downward and the slots widen.

Figure 6 and Figure 7 show that lift and moment coefficients of multi-element airfoils vary with flap displacement, in which lift coefficients change clockwise and moment coefficients change counterclockwise. Because of the small amplitude of flap, the variation range of lift coefficient and moment coefficient is not large. The maximum variation range of lift coefficient is $0.7\%$, and the maximum variation range of moment coefficient is $1.6\%$. This is because the flap contribute less to lift, and because the flap are far away from the moment reference point (1/4 chord point of the original airfoil), the flap contribute more to the moment. Therefore, the flap vibration has a greater influence on the moment coefficient.
With the increase of the amplitude, the variation range of lift coefficient and moment coefficient gradually increases, but the hysteresis loop curve is basically similar at the same frequency; with the increase of frequency, the variation range of lift coefficient and moment coefficient gradually decreases, and the hysteresis loop gradually becomes "thin" and its shape tends to ellipse.

When the frequency equals 5 Hz, the unsteady effect of flow field is small, and the lift and moment coefficients of wide slot are larger than those of narrow slot. With the increase of frequency, the unsteady effect increases significantly, and the difference between the lift and moment coefficients of the widest and the narrowest slots becomes smaller or even reverses (as shown in Figures 6 (a), 6 (b), 6 (c), 7 (a)).
4. Conclusion
The unsteady aerodynamic forces of the flap of 30P30N multi-element airfoil are studied. Because the chord length of the flap is only 30% of the original airfoil, the influence of the flap vibration on the overall lift coefficient of the multi-element airfoil is small, and because the flap are far from the moment reference point, the pitch moment coefficient of the flap vibration is relatively large. The hysteresis loops of lift and moment coefficients at the same frequency and different amplitudes are basically similar. With the increase of flap vibration frequency, the unsteady effect of flow field increases, and the variation of lift and moment coefficients of different slots may be contrary to that of steady flow.

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