Wake behavior analysis of partial-span flaps using free-wake method with gap model

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Nomenclature

ϕ	= velocity potential
Γ	= strength of bound vortex
Γ_w	= strength of nascent wake vortex
$\vec{r}$	= position vector
$\mathbf{n}$	= normal vector of vortex ring element
Δt	= time step
c	= chord length
b	= span length
α	= angle of attack
C_L	= lift coefficient
M_∞	= Mach number of freestream

I. Introduction

WAKE vortices that develop behind fixed aircraft and rotorcraft contain intense circulations, and the disturbances propagate downstream, producing pressure fluctuations. The strong tip vortices generated from a heavy airplane can pose a hazard to the following aircraft. Hence, the U.S. Federal Aviation Administration (FAA)

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has enacted the standards for separation distance between the leading and following aircraft for wake turbulence avoidance [1]. Technologies for alleviating wake vortices produced behind lifting surfaces have been critical for aircraft safety [2]. Previous researches showed the considerable potential of flow control to destabilize wake vortices intentionally using additional active or passive devices [3–5]. In particular, the flap system is an efficient approach to creating an unstable vortex system and triggering a fast breakdown of the inherent wake structures. As a result, wake intensity rapidly diminishes, and the hazard level associated with strong interaction reduces significantly with increasing distance from the lifting surfaces [6]. Abe *et al.* [7] demonstrated an active flow control for deflecting a direction of wake structures behind a NACA 0012 airfoil using an active morphing flap. Ortega *et al.* [8] examined the wake alleviation properties of wings with outboard-triangular flap extensions through particle image velocimetry (PIV) measurements in a towing tank. Matalanis and Eaton [9] conducted wind-tunnel experiments and complementary computations to study the feasibility of actuated Gurney flaps for wake alleviation. Traub [10, 11] observed that the deflection of plain trailing-edge flaps induces an earlier onset of vortex breakdown in the wake of delta wings.

Although experimental investigation is able to analyze the complex wake dynamics, the high consumption of resources makes it unfeasible for many applications. Therefore, the computational tools are needed for developing an effective wake alleviation technique, particularly in the initial design stages. The vortex lattice method (VLM) can describe the unsteady evolution of wake structures even at far distances, owing to its ability to neglect the numerical dispersion error [12]. These features are competitive advantages for simulating unsteady and complex wake flows, compared to other conventional grid-based computational fluid dynamics (CFD), such as Reynolds-averaged Navier–Stokes equations (RANS) simulation. Therefore, VLM can be applied for simulating the lifting surfaces with spoiler or flap systems. Xu and Yeung [13] developed a discrete vortex method with a new formulation for sharp-edge conditions to simulate the mutual interaction between shedding vortices from the spoiler tip and airfoil trailing edge, which gives rise to a highly turbulent oscillatory wake. Rubbert [14] proposed the non-planar VLM for simulating the wing-flap configuration. Even though this model provides improved results compared to the simulations without wing-flap treatment, nonphysically concentrated vortices were generated at the wing-flap-free edges. Rajeswari and Dutt [15] suggested a gap model based on a discrete horseshoe vortex method (HVM) to resolve this problem. However, this gap model has a severe limitation in that it can be applied only for the steady-state condition because the HVM describes only trailed wake vortices without considering the shed wake vortices. The strength of the trailed vorticity is determined by the difference between the bound vortices along the spanwise direction. In contrast, that of the shed vorticity depends on the change in the bound vorticity with time.

This paper proposes a wing-flap gap model extended from the work of Rajeswari and Dutt [15]. Our model is based on VLM for describing unsteady wake structure generated between the wing and flap region, considering both trailed and shed vortices. The lifting surfaces, including the wing and flap, were modeled with a discrete vortex lattice. The aerodynamic loads and the strength of the bound vortices on the lifting surface were determined by VLM simulation. At each time step, the trailed and shed vortices modeled by the vortex filaments were generated at the trailing edges of the wing and flap and the wing-flap gap. A rectangular wing with plain flap configuration was simulated, and the predicted lift coefficients were compared with the wind tunnel experiment data. The behavior of the trailing wake structures was investigated by comparing VLM simulations with and without the gap model.

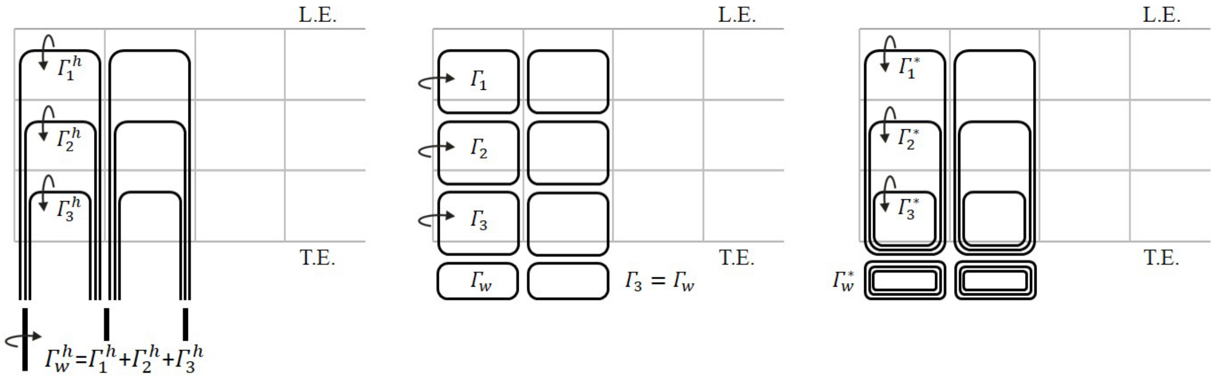
II. Numerical methods

A. Vortex lattice method

The VLM is based on assuming the thin lifting surface theory. The mean camber surfaces of the lifting body are modeled as an infinitely thin sheet of discrete vortices, and the influence of body thickness is neglected. In the VLM simulation, a constant-strength vortex distribution with a strength of circulation (Γ) is used to model the lifting surface as in Eq. (1).

$$\phi(\vec{x},t)=\frac{1}{4\pi}\int_{S_{wing+wake}}\Gamma(s,t)\,\mathbf{n}\cdot\nabla\left(\frac{1}{r}\right)dS \qquad \text{Eq. (1)}$$

Figure 1 shows three types of wing modeling methods using discrete vortex elements. Fig. 1(a) is the HVM for the steady simulation, whereas Fig. 1(b) is a conventional VLM for unsteady simulation. A different modeling method for unsteady simulation is shown in Fig. 1(c), an unsteady VLM using vortex ring elements. Although the second and third type models are mathematically identical, the circulation relations of the bound and nascent wake vortices are different. By enforcing the Kutta condition at the vortex elements located at the trailing edge of the wing, the strengths of the nascent wake vortices Γ_w in Fig. 1(b) and Γ_w^* in Fig. 1(c) are evaluated by Eqs. (2) and (3), respectively.



(a) (b) (c)

Fig. 1. Wing modeling method using discrete vortices: (a) HVM, (B) VLM (type 1), and (c) VLM (type 2)

$$\Gamma_W = \Gamma_1 + (\Gamma_2 - \Gamma_1) + (\Gamma_3 - \Gamma_2) \qquad \text{Eq. (2)}$$

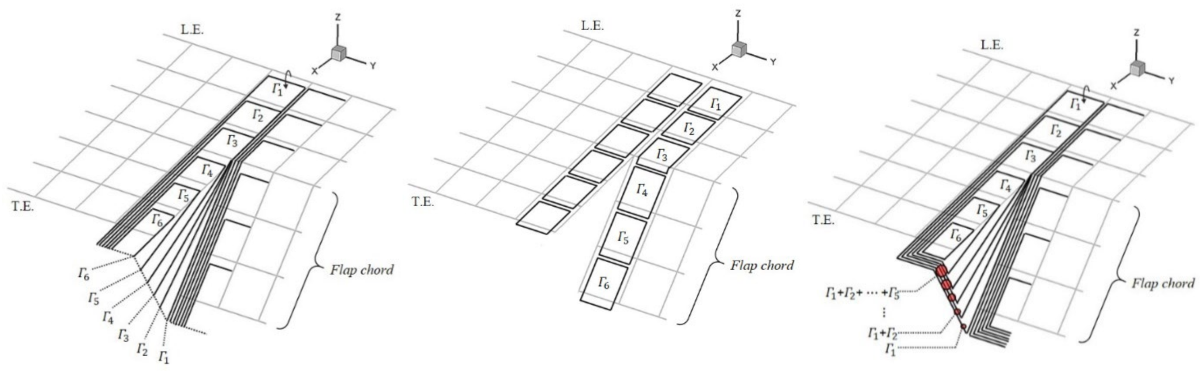
$$\Gamma_W^* = \Gamma_1^* + \Gamma_2^* + \Gamma_3^* \qquad \text{Eq. (3)}$$

In this work, the VLM in Fig. 1(c) is utilized to represent the lifting surfaces of the wing flap configuration because the VLM in Fig. 1(b) has difficulty describing the shed wake vortices developed from the gap region between the wing and flap. In addition, the time-marching free-wake method with the wing-flap gap model is suggested for modeling the wing-flap wake vortices.

B. Wing-flap gap model

For the steady simulations, the influence of the shed vortex can be negligible. However, the shed vortex should be considered for the unsteady simulation of the fixed-wing with flap configuration, as it directly affects the wing aerodynamics and wake dynamics. The trailing and shed vortices are generated from the wing's trailing edge and a geometric discontinuity between the wing and deflected flap. Therefore, the gap modeling is required to capture the wake structures of the wing flap and describe their evolution downstream. In this study, the wing-flap gap model based on VLM with the time-marching free-wake method was proposed to analyze wake behavior of the wing with partial-span flap.

Figure 2 shows the wing-modeling methods using discrete vortex elements. Rajeswari and Dutt [15] modeled the gap between the wing and deflected flap using discrete horseshoe vortices to diffuse two concentrated trailing vortices, as shown in Fig. 2(a). The trailing vortex of the leading-edge adjacent to the flap row elements (left side of the wing-flap gap region) is positioned on the trailing vortex line of the flap tip, whereas the other trailing vortices in the same row are spread and cover the wing-flap gap on a sheet in the same interval. Compared to the VLM without a gap model as shown in Fig. 2(b), although the gap model using discrete horseshoe vortices can prevent lift losses at the wing-flap region, this model is not suitable for the unsteady simulation of wake flows because the shed vortices cannot be considered. Fig. 2(c) shows the newly proposed gap modeling method using vortex ring elements, a modified version of the gap model proposed by Rajeswari and Dutt [15] where the discrete horseshoe vortices are replaced by vortex ring elements. The trailing vortices from the wing are deflected, and they cover the gap region between the wing and flap. The influences of the trailing vortices generated from the flap gap are included for calculating the influence coefficient matrix. In addition, the strength of the shed vortex close to the flap is the same as the vortex near the leading edge, and the adjacent shed vortices are added individually to the trailing vortices from the panels on the wing. If the flap deflection angle is zero, the proposed VLM with the gap model (Fig. 2(c)) becomes the VLM model for only wing simulation shown in Fig. 1(c). In this study, we simulated the rectangular wing with plain flap configuration using both modeling methods, as shown in Figs. 2(b) and 2(c), and the lift coefficients and wake dynamics are discussed to validate the proposed gap model.



(a) (b) (c)

Fig. 2. Wing-flap gap modeling methods: (a) HVM with gap model [15], (b) VLM without gap model, and (c) VLM with gap model

III. Results and discussion

A. Lift coefficients of partial-span plain flaps

The National Advisory Committee for Aeronautics (NACA) technical note [16] reported the results of a wind tunnel measurements for a semi-span wing with plain flaps. The wing has an unswept and untapered configuration and its sectional profile is NACA 64A010. The semi-span and the chord length are 3.875 ft. (1.181 m) and 2.5 ft. (0.762 m), respectively, and the corresponding aspect ratio is 3.1. The dimension of flap is one-quarter of the chord and span length, and the flap deflection angle is 30°. The wind tunnel experiments were performed at Mach number (M_∞) of 0.27. The lift coefficients calculated from the numerical simulation were corrected by dividing by $\sqrt{1 - M_\infty^2}$ based on the Prandtl–Glauert rule [17] to consider the compressibility effects. The number of grid used for the simulation is 120 × 20 in the spanwise and chordwise directions, respectively.

Figure 3 shows the comparisons of the lift coefficients predicted from VLM simulations with and without the gap model for the plain flap on the outboard sections of the rectangular wing. The lift coefficients predicted from VLM simulation with the gap model are well-matched with the experimental data except at a high angle of attack. It indicates that the proposed gap model can consider the flap effects on the variation of the lift coefficients with angle of attack. However, in the case where the gap model is not applied, the lift coefficients are under-predicted owing to the negative forces generated at the gap region between the wing and flap.

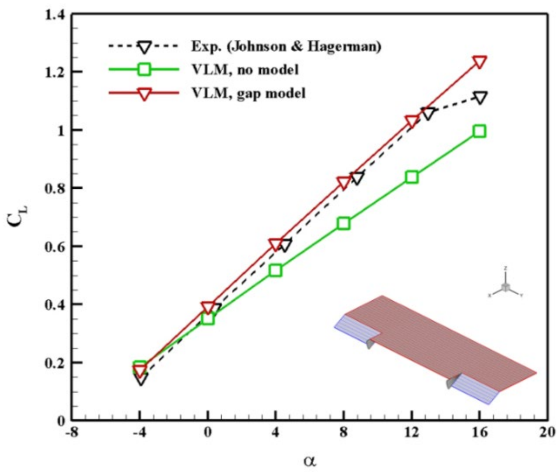
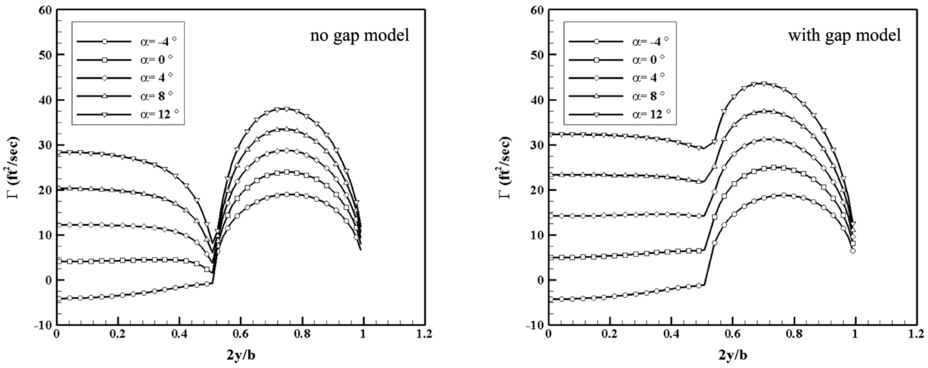


Fig. 3. Comparison of the lift coefficients of the rectangular wing with partial-span plain flaps

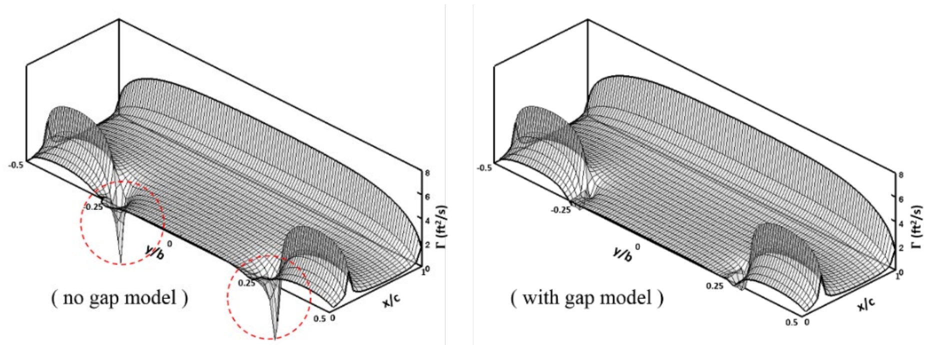
Figure 4 shows the variation of the chord-wise integrated circulation along the wing span. A similar circulation distribution is obtained from both VLM simulations with and the without the gap model at the angle of attack of -4°, which results in a similar lift coefficient as shown in Fig. 3. This is because the strength of the vortex filaments generating from the wing-flap gap is close to zero, so that the effect of the gap model is negligible. However, when the angle of attack is positive and the gap model is not considered, nonphysically concentrated vortices are captured owing to a steep gradient of circulation at the side edges of the wing and the deflected flaps. Fig. 5

indicates the strength distributions of the bound vortices on the lifting surfaces at the angle of attack of 8°. The simulation results of VLM without the gap model showed significant negative peak values of the circulation with a discontinuous distribution that leads to the inaccurate prediction of the trailing wake structure and its intensity at the wing-flap location.



(a) (b)

Fig. 4. Comparison of the variation of chord-wise integrated circulation along the span: (a) VLM without gap model and (b) VLM with gap model



(a) (b)

Fig. 5. Comparison of the circulation distributions on the lifting surface at the angle of attack of 8°: (a) VLM without gap model and (b) VLM with gap model

B. Investigation of wake structure

The wake structures behind the lifting surface are modeled using a time-marching free-wake method and their strength is determined by imposing the Kutta condition. Fig. 6 shows the comparison of x-vorticity contour behind the outboard sections of the wing at an angle of attack of 8°, where the contours are calculated downstream at *x/b* = 3. The three-strong vortices generated from wing tip, flap and the wing-side free edge are captured when the gap model is not applied for VLM simulation. However, only two strong vortices are generated when the gap model is considered. It indicates that a relatively strong flap vortex and wing-side free edge vortex have opposite sign circulation. The gap model provides the de-intensified flap vortex by merging these two vortices.

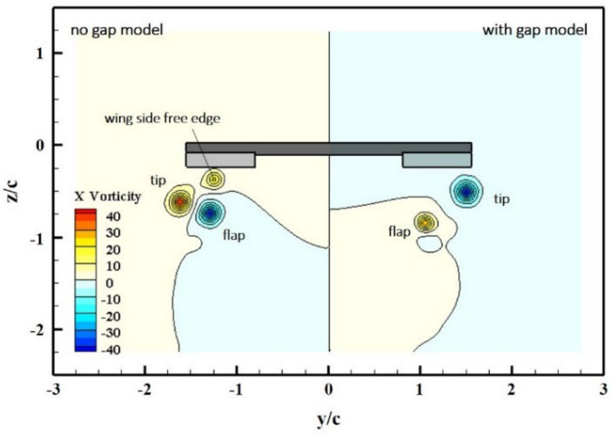


Fig. 6. Comparison of the wake vortices behind the outboard sections of the wing at x/c = 3 and angle of attack of 8°

Figures 7 and 8 show the wake trajectories of the rectangular wing with the outboard plain flap at various angles of attack. The strength of the trailing wake vortices originated from the wing-side free edge gradually increases as the angle of attack increases, and these vortices interact with the flap wake vortices. The physical meaning of the gap model is that the two concentrated vortices are generated at the geometrical discontinuity between the wing and deflected flaps, mainly spreading into discrete wing vortices. Similar wake structures are observed at the low angle of attack ranging from −4° to 4° because the strength of the wing vortices is relatively weak, and the spreading effect by the gap model is not significant. However, the evolution of the wake structures are different significantly depending on the use of the gap model at higher angles of attack. When the gap model is not applied for VLM simulation, each vortex pair produced by the deflected flap moves similarly to a single vortex pair because the strengths of the trailing vortices are nearly identical. The vertical position of the vortex pairs gradually decreases as wake vortices evolve downstream. When the gap model is implemented, the wake vortices generated from the wing tip and flap strongly interact each other, and the weaker flap vortices rotate around stronger tip vortices. Furthermore, it is observed that the weaker flap vortices move faster around the tip vortices in a spiral trajectory as the angle of attack increases.

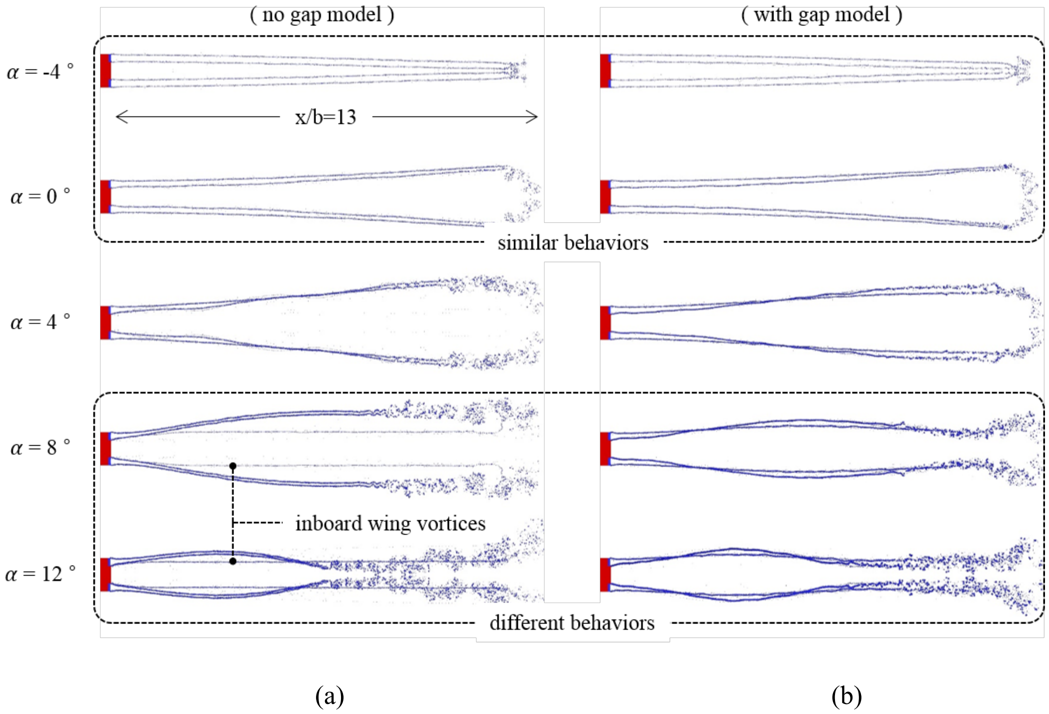


Fig. 7. Comparison of the top view of the wake structures of the wing with deflected flaps: (a) VLM without gap model and (b) VLM with gap model

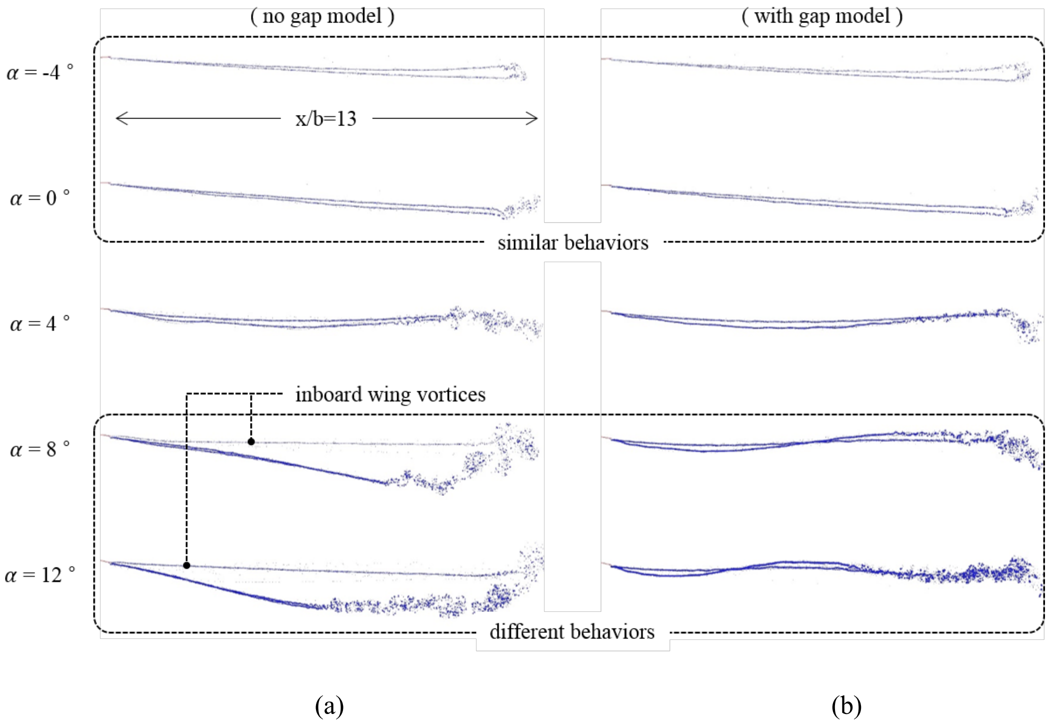


Fig. 8. Comparison of the side view of the wake structures of the wing with deflected flaps: (a) VLM without gap model and (b) VLM with gap model

IV.Conclusion

This paper proposed a new gap-modeling method based on VLM to predict the aerodynamic load and the wake trajectories of a rectangular wing with plain flaps. The lifting surfaces, including wing and flap, were modeled using vortex ring elements, and the evolution of the wake structures generated from the wing, flap, and wing-flap gap was described using a time-marching free-wake method. The plain flap on the outboard sections of the rectangular wing was simulated at various angles of attack to validate the proposed wing-gap model. The validation results showed that the VLM simulation with the gap model provided more accurate prediction of the lift coefficients than the simulation without the use of the gap model. In addition, the circulation distribution on the lifting surfaces, vorticity fields, and wake trajectories were compared to prove the feasibility of the proposed gap model. The numerical results demonstrated that physically reasonable solutions of wake behavior behind the wing-flap configurations can obtained by implementing the gap model.

The present work focused on the application of a gap model based on VLM to investigate wake behavior of fixed wing with deflected partial-span plain flaps. A limitation of this study is that unsteady motion of flap system has not been considered. This gives scope for further research on developing more advanced wake alleviation methods. The effects of the unsteady flap motions, such as rotor blades equipped with an active flap system, on the wake trajectory and its stability characteristics will be analyzed in our future study.

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