A TIME-DOMAIN PANEL METHOD FOR UNSTEADY SUBSONIC COMPRESSIBLE AERODYNAMICS

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ABSTRACT

To evaluate the subsonic aerodynamic characteristics of aircraft in aeroelasticity, the unsteady vortex lattice method (UVLM), double lattice method (DLM) and computational fluid dynamics (CFD) are commonly employed. CFD excels at complex flows but is computationally expensive. As low-fidelity methods, UVLM and DLM are widely used in subsonic aeroelasticity but also have limitations: UVLM, extended to compressible flows via Prandtl-Glauert transformation, exhibits accuracy deficiencies in unsteady cases; DLM, computing time-domain aerodynamic forces in conjunction with Rational Function Approximation (RFA), fails at spiral-shaped gust aerodynamics, has constrained wake shapes affecting calculation accuracy and struggles with nonlinear structures owing to the modal assumption.

To resolve these issues, this paper proposes a time-domain compressible panel method. The small-disturbance linearized compressible potential flow equation is adopted as the governing equation, and the source and double lattice fundamental solutions with time delay terms are derived accordingly. For wake modelling, in incompressible cases, the first two rows of wake vortex lattices are retained to preserve induced vortices at side edges of the airfoil, while the subsequent vortex lattices are equivalent to a vortex line and multiple vortex particles. In compressible cases, however, wake vortex lattices will cause calculation divergence due to the presence of time delay terms. Therefore, all vortex lines forming the wake vortex lattices are converted into vortex particles as shown in Fig.1. In addition, since the high-order geometric function $\chi(r;\sigma)$ is used in the induced velocity calculation formula of vortex particles to replace $1/r^3$ (the comparison is shown in Fig.2), and the integral of vortex line intensity is directly equivalent to the product of vortex line length and vortex intensity, there are nonnegligible errors when calculating the induced velocity near the vortex particles, leading to a significant decline of accuracy in the wake interference region. For this reason, when vortex particles approach the subsequent airfoil, they need to be split into multiple smaller particles, and the normalized parameter σ is adjusted accordingly. Then, the transient aerodynamic response under arbitrary motions can be solved through four steps: wake generation, airfoil panel intensity calculation, aerodynamic force calculation, and wake rolling-up calculation.

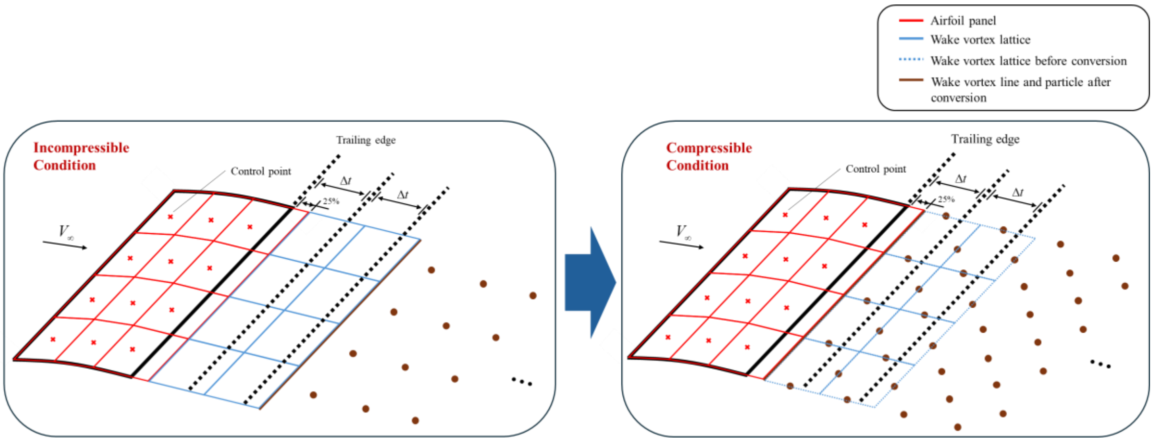


Fig.1 Schematic diagram of airfoil and wake under incompressible/compressible conditions

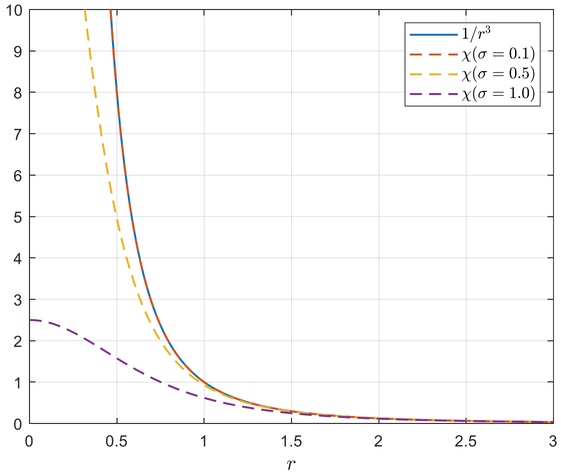
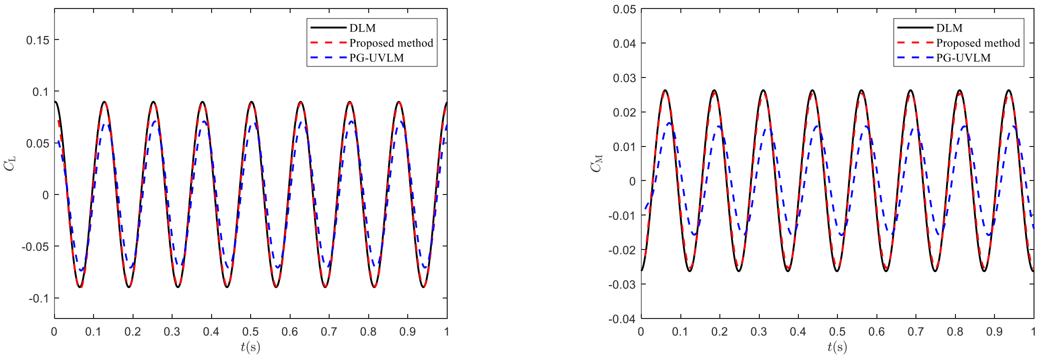


Fig.2 Comparison between high-order geometric function $\chi(r;\sigma)$ and $1/r^3$

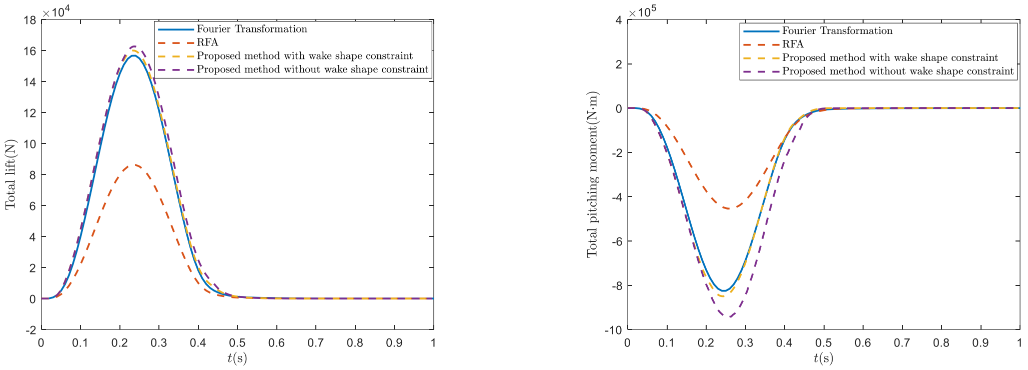
To illustrate the accuracy of the proposed method, UVLM with Prandtl-Glauert transformation (PG-UVLM), DLM and the proposed method are used to calculate the lift and pitching moment of a flat wing under pitching and heaving motions at 2 Hz, 4 Hz, 6 Hz, and 8 Hz with Ma being 0.0 and 0.6 respectively. At 0.0Ma, three methods show good agreement with a peak error of 5%. At 0.6Ma, as the motion frequency increases, the calculation accuracy of PG-UVLM in both amplitude and phase decreases significantly as shown in Fig.3, while the error between DLM and the proposed method is always within 5%. Regarding gust aerodynamics, a half-model configuration with a wing and a horizontal tail is adopted, and DLM is used to compute the frequency-domain gust aerodynamic forces at 0.6Ma (with free stream velocity being 190 m/s). Then, the time-domain responses of total lift, total pitching moment, wing root bending moment and tail root bending moment under discrete gust with a scale of 75 m and an amplitude of 12 m/s are obtained through Fourier Transformation and RFA respectively. Meanwhile, the proposed methods with/without the same wake shape constraint as DLM are used to calculate the aerodynamic forces under identical discrete gust. Result comparison is shown in Fig.4, which illustrates that due to the spiral shape of the frequency-domain aerodynamic forces, RFA accuracy is insufficient with an error of more than 40%. In addition, the calculation results of the proposed method with wake shape constraint are consistent with those of Fourier Transformation. However, after releasing the wake shape constraint, the aerodynamic forces of the horizontal tail increase significantly. Although the wake shape constraint is reasonable when the gust velocity or the distance between the wing and the tail is very small, the wake shape results of this case shown in Fig.5 indicate that the wake vortex particles are lifted by the gust and have a significant vertical displacement which weakens the downwash on the horizontal tail. Therefore, for maneuvering conditions or gust conditions involving wake interference (the velocity disturbance may still be within the small-disturbance assumption), more attention should be paid to the impact of wake deformation on the aerodynamic force calculation. Finally, a high-aspect-ratio wing with a folding wingtip is adopted to conduct gust response analysis using structural mode-DLM, structural mode-proposed method and geometrically exact beam theory-proposed method respectively. It is indicated that due to the large deformation of the inner wing, the rotation of the wingtip and the wake deformation, there are certain differences in the calculation results among the three methods. In addition, this case illustrates the advantage of the proposed method in combining nonlinear structural theories for aeroelastic analysis.



a) Lift coefficient response

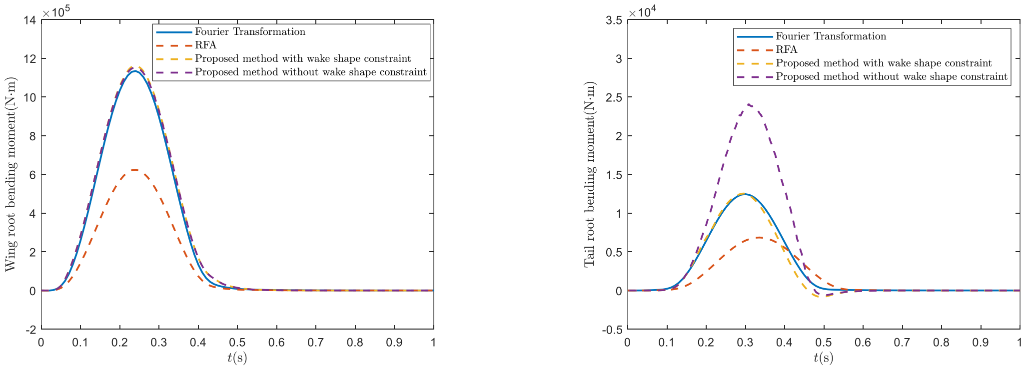
b) Pitching moment coefficient response

Fig.3 Lift coefficient and pitching moment coefficient responses of 8 Hz heaving motion



a) Total lift response

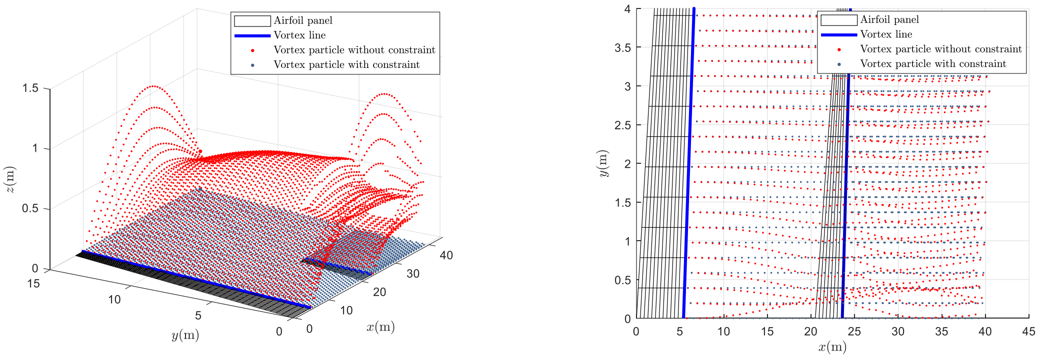
b) Total pitching moment response



c) Wing root bending moment response

d) Tail root bending moment response

Fig.4 Comparison of aerodynamic forces under discrete gust



a) 3D plot

b) Top view

Fig.5 Wake shape under discrete gust

In summary, this paper proposes a time-domain compressible panel method based on the compressible potential flow equation, and the wake model is improved to address the time-delay characteristics and wake interference. Furthermore, three validation cases demonstrate the accuracy of the proposed method, along with its advantages in gust aerodynamic force calculation, wake interference calculation and co-simulation with nonlinear structural models. Future work will focus on: 1) Due to the significant increase in the number of wake particles, the computational cost has also increased. Therefore, it is necessary to develop an adaptive merging and splitting algorithm for wake particles to improve computational efficiency; 2) The current method does not consider viscous effects, so it is necessary to introduce a viscous dissipation model to enhance the applicability of the method in low-Reynolds-number flows.