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New Blockage-Correction Method for Separated Flows in a Subsonic Wind Tunnel

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Introduction

WALL-INTERFERENCE-CORRECTION methods can be categorized into the classical method, the computational-fluid-dynamics method, the measured-boundary-condition method, and the adaptive wall method. Currently, the classical method and the measured-boundary-condition method are most widely used because of the superior productivity of data and the operational simplicity. The classical method is easy and efficient to use because additional measurements are not required for the correction and works well for conventional simple aircraft models of a small size up to moderate angles of attack. However, at high angles of attack, the classical method is known to have a tendency of overcorrection and thus can be used only as a qualitative guidance.[1–4]

The measured-boundary-condition method can be applied to any model configurations, including internal devices such as the model support and the sting. It is generally accepted that the correction made by the measured-boundary-condition method is more reliable than the classical method at high angles of attack. However, this method requires expensive instrumentations, large computer time, and pretests for database construction.[1,3,4]

Although the flight envelope of conventional aircrafts is mostly restricted to moderate angles of attack below stall, modern fighters are designed to perform high angle-of-attack maneuver at poststall regions. To reduce the time and the cost involved in the design cycle of a new aircraft, the test data from wind-tunnel testing must be provided to the designer as quickly and accurately as possible.[5] Thus, a fast, efficient, and reliable wind-tunnel wall correction method that works well for both moderate and high angles of attack involving flow separation is urgently required.

In the present study, a new separation blockage correction method for aircraft configurations has been developed for subsonic wind tunnels with a closed test section. For this purpose, a nonlinear relationship between the separation drag coefficient and the separation blockage correction was obtained based on the test results of a combat aircraft configuration. The present method was validated by comparing the corrected results with those of the classical method and the measured-boundary-condition method.

Classical Blockage-Correction Methods for Separated Flows

The blockage effect of the separated flow on the wind-tunnel test data is typically corrected by using an empirical formula based on the test results of bluff bodies with edge separation. An experimental study about bluff-body flows in a closed test section was conducted by Maskell[6] for flat plates of various aspect ratios installed normal to the stream. The results showed that the separation blockage ϵ_{sep} can be evaluated as

$$\epsilon_{\text{sep}} = \tfrac{1}{2}\theta(S/A_T)C_{D_s} \qquad (1)$$

where A_T, S, and C_{D_s} represent the test section area, the reference area, and the separation drag coefficient, respectively. The value of the separation blockage factor θ was suggested by several reseachers as follows:

$$\begin{aligned} &\theta = 2.5 && \text{(Maskell}^6\text{)} \\ &\theta = 2.8 - 0.068\mathit{AR} && \text{(Vayssaire}^7\text{)} \\ &\theta = 0.96 + 1.94e^{-0.06\mathit{AR}} && \text{(Cooper}^3\text{)} \\ &\theta = 1.7 && \text{(Peitzmann}^8\text{)} \end{aligned} \qquad (2)$$

where AR is the aspect ratio of the wing.

Hackett and Cooper[3,9] extended the Maskell's separation blockage theory[6] by accounting for the effect of separation bubble distortion on the separation drag in estimating the separation blockage.

New Separation Blockage-Correction Method

As the angle of attack increases, the flow starts to separate from the surface of the aircraft model. However, the pattern of the flow separation is highly dependent on the model configuration and its attitude and is very different from that of a flat plate characterized by edge separation. Thus, the Maskell's method[6] based on the separated flows of flat plates is not adequate for full aircraft models. The separation blockage factors suggested by Vayssaire[7] and Cooper[3] also have a similar problem because those factors were obtained by curve fitting the Maskell's data.

Ashill and Keating[10] conducted a wind-tunnel testing of a half-span combat aircraft configuration and demonstrated that the separation blockage has a nonlinear relationship with the separation drag coefficient as shown in Fig. 1. The figure also confirms that Maskell's separation blockage factor of 2.5 is too large and has an overcorrection problem. The value of 1.7 proposed by Peitzmann[8] is similar to the slope of the test result when the separation drag coefficient is between 0.3 and 0.8. However, the estimated separation blockage is consistently higher than the test result.

To estimate the separation blockage factor more accurately, the test result obtained by Ashill and Keating[10] is substituted into

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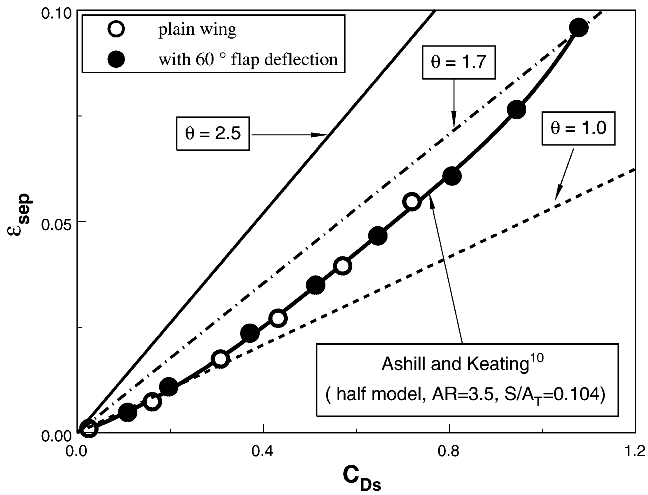


Fig. 1 Separation blockage vs separation drag coefficient for a half-span combat aircraft configuration.

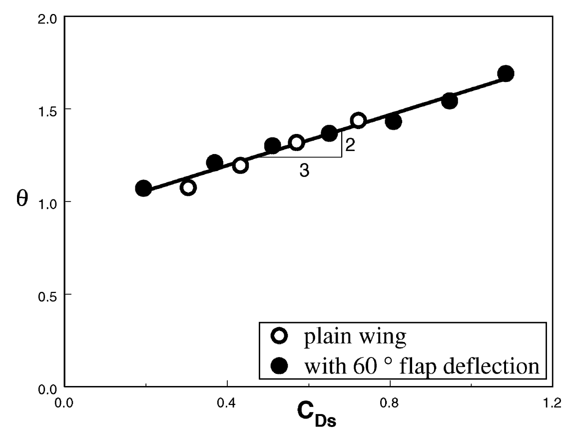


Fig. 2 Relationship between separation blockage factor and separation drag coefficient based on Ashill and Keating's test results.[10]

Eq. (1), and an approximately linear relationship between the separation drag coefficient and the separation blockage factor is obtained as shown in Fig. 2. At zero separation drag coefficient, the factor is set to one as suggested by Ashill and Keating.[10]

$$\theta = 1 + \tfrac{2}{3} C_{D_s} \tag{3}$$

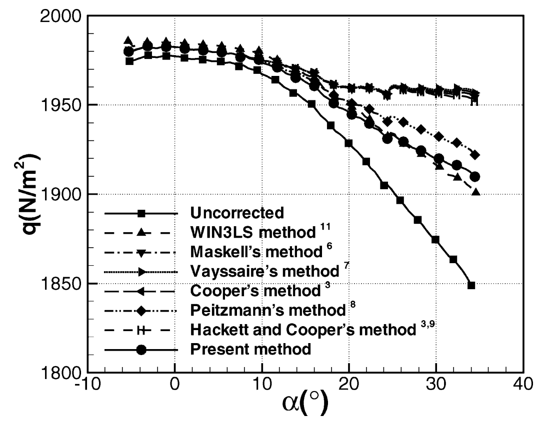
From this relationship, the separation blockage can be represented as a second-order nonlinear function of the separation drag coefficient.

$$\epsilon_{\text{sep}} = \tfrac{1}{2}\left(1 + \tfrac{2}{3} C_{D_s}\right) C_{D_s} (S/A_T) \tag{4}$$

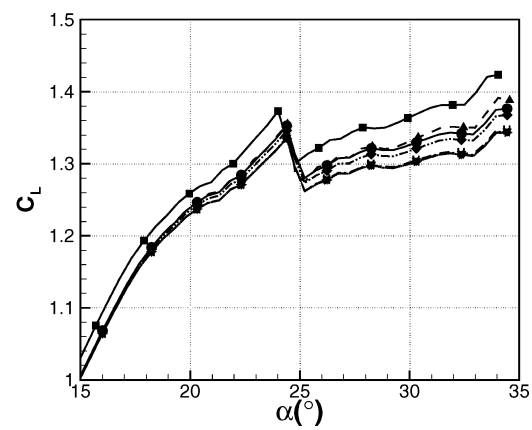
Results and Discussion

The present nonlinear separation blockage correction method was applied to the test data of a jet-trainer model[11] obtained from the DNW-LST (Duits-Nederlandse Windtunnels-Low Speed Tunnel) having a closed test section of 3 m(W) × 2.25 m(H). The reference blocking area S/A_T was 3.7%, and the freestream velocity was 56 m/s. For validation, the result was compared with those of the classical separation blockage correction methods[3,6–9] and the WIN3LS method,[11,12] a measured-boundary-condition method developed by DNW. In this comparison, the solid and wake blockages and the buoyancy and lift interferences for the classical methods were estimated based on the same correction method.[1,2] The wall-pressure distribution for the WIN3LS method was measured using pressure strips with 23 pressure holes attached at four locations on the starboard side of the test section surface.[11]

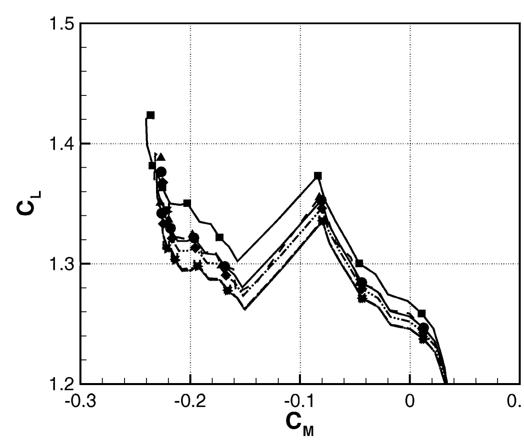
In Fig. 3, the dynamic pressure and the lift and pitching-moment coefficients corrected by the present method are compared with the uncorrected data and those of other correction methods. It shows that the corrected results by all methods are almost the same at the attached flow region. However, at the separated flow region the difference in the corrected results between the classical separation blockage correction methods and the WIN3LS method becomes significantly large, whereas the results by the present method are in good agreement with those of the WIN3LS method at all angles of attack. The Peitzmann's method deduced from an aircraft wind-tunnel test results[8] shows slightly better correction than other classical methods based on the bluff-body flows. The results of the Hackett and Cooper's method are also similar to those of the Maskell's method for this aircraft configuration, even though the method is known to be more accurate than the Maskell's method for nonlifting flat plates at large blockage[3] and flat-plate wings up to 110-deg angle of attack.[9] At an angle of attack of 34 deg, the increments of the dynamic pressure predicted by the Maskell's and Peitzmann's methods were approximately 95 and 38% higher than



a) Dynamic pressure vs angle of attack



b) Lift coefficient vs angle of attack



c) Lift coefficient vs pitching moment coefficient

Fig. 3 Comparison of the corrected results for a jet-trainer model.[11]

that of the WIN3LS method, respectively, while the difference between the present method and the WIN3LS method was approximately 15%. The corrected lift coefficients by the Maskell's and Peitzmann's methods were approximately 2.4 and 1.1% lower than that of the WIN3LS method at the poststall region. However, the difference between the present method and the WIN3LS method was less than 0.5%. Similarly, the corrected pitching-moment coefficients by the Maskell's and Peitzmann's methods at the separated flow region were approximately 2.6 and 1.3% higher than that of the WIN3LS method, whereas the difference of the present method was less than 0.8%.

Conclusions

In the present study, a new separation blockage correction method has been developed for the accurate wall correction of the dynamic pressure for realistic aircraft models. This method can be applied continuously from the low-angle-of-attack region to the highly nonlinear poststall region. It was shown that the results by the present correction method based on the nonlinear relationship between the separation blockage and the separation drag are in good agreement with those of the measured-boundary-condition method. The present separation-blockage-correction method provides accurate wall correction for separated flows around realistic aircraft configurations for closed test-section subsonic wind tunnels.

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