Correction of Wind Tunnel Test Data for Additional Roughness Drag*

Hidetoshi IIJIMA,1† Masayoshi NOGUCHI,2† and Shinji NAGAI1†

1Japan Aerospace Exploration Agency, Chofu, Tokyo 182–8522, Japan
2Japan Aerospace Exploration Agency, Mitaka, Tokyo 181–0015, Japan

A method to correct wind tunnel test data for the additional drag caused by roughness elements in a fully turbulent boundary layer is proposed using drag polar curves obtained from wind-tunnel tests. It is assumed that boundary layer over a wind tunnel model is fully turbulent at high absolute angle of attack both with and without roughness elements from the results of measurements using Preston tubes, and that the additional drag due to the roughness elements is constant over the entire range of the angle of attack. The additional roughness drag is estimated using the axial force data obtained from internal balances. The method proposed was validated using the data from wind tunnel tests with the same Mach number with two models obtained from two different wind tunnels. The differences in the values of minimum drag coefficient obtained from the two wind tunnels tests corrected by this method were smaller than those corrected using a conventional method, and they were well within the uncertainties in terms of the drag coefficient. Furthermore, the additional roughness drag can be estimated by this method when applying wind tunnel data obtained using only a single roughness height.

Key Words: Wind Tunnel Testing, Roughness Elements, Drag Coefficient

Nomenclature

\[ C_A: \] axial force coefficient
\[ C_D: \] drag coefficient
\[ C_{D_{\text{min}}}: \] minimum drag coefficient
\[ C_N: \] normal force coefficient
\[ C_f: \] skin friction coefficient
\[ C_L: \] lift coefficient
\[ C_m: \] pitching moment coefficient
\[ C_p: \] pressure coefficient
\[ k: \] roughness element height
\[ M: \] Mach number
\[ P_0: \] total pressure
\[ P_b: \] base pressure
\[ Re: \] Reynolds number
\[ S: \] reference area
\[ \alpha: \] angle of attack

1. Introduction

Wind tunnel tests are normally conducted at lower Reynolds numbers than in-flight conditions because of facility limitations. Although the boundary layer on an aircraft may be fully turbulent at the Reynolds number corresponding to full-scale flight, extensive regions of laminar boundary layer may exist on a scale model in a wind tunnel. Moreover, it is difficult to directly compare wind tunnel test data with computation fluid dynamics (CFD) data for fully turbulent flows. To address this issue, roughness elements are often attached to the leading edges of the wing and forward fuselage of wind tunnel models to trip the boundary layer from laminar to turbulent flow. However, such roughness elements may cause additional roughness drag. Since the minimum drag coefficient \( C_{D_{\text{min}}} \) during cruise conditions is a critical parameter in aircraft development, it is important to use wind tunnel testing to estimate the fully turbulent \( C_{D_{\text{min}}} \) that does not include the additional drag caused by the roughness elements.

The Japan Aerospace Exploration Agency (JAXA) has conducted wind tunnel tests for development of the Silent SuperSonic Technology Demonstrator (S3TD). The same model was tested using the same balance in two wind tunnels: the JAXA 1 m \( \times \) 1 m supersonic wind tunnel (JSWT) and the JAXA 2 m \( \times \) 2 m transonic wind tunnel (JTWT). The \( C_{D_{\text{min}}} \) values obtained from measurements taken in the two wind tunnels at the same Mach number of 1.4 differed slightly. This discrepancy is considered to be caused by the differences in (1) skin friction drag caused by unknown turbulent boundary layer regions and (2) drag caused by roughness elements, in addition to the variation in skin friction caused by the difference in the Reynolds numbers in the two wind tunnels. A laminar run correction method\(^1\) has been proposed to determine the skin friction drag caused by the unknown turbulent boundary layer regions. The transition locations are first determined, and then the skin friction of the laminar flow regions is substituted with that of a turbulent boundary layer using the formulae for skin friction on a flat plate. However, it is very difficult to precisely identify the transition locations. Further, the repeatability of the data is poor since the boundary layer is unstable without roughness elements, so the transition locations can vary. Even if the transition locations are fixed by roughness elements, it is necessary to correct for the additional roughness drag. An extrapolation method\(^2\) has therefore been proposed. In this

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\[ \dagger \] Corresponding author, iiijima@chofu.jaxa.jp

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method, the value of $C_{D_{\text{min}}}$ at zero roughness height is estimated from several values of $C_{D_{\text{min}}}$ obtained using roughness elements with different heights. This process is very time-consuming in a wind tunnel test campaign because it requires repeated measurements of $C_{D_{\text{min}}}$ with roughness elements of different heights attached to the model.

This paper proposes a simplified method to correct the values of fully turbulent $C_{D_{\text{min}}}$ for the additional roughness drag. It is assumed that the boundary layer at high absolute angles of attack will be turbulent regardless of whether or not roughness elements are present. This is because the boundary layer transition point tends to move forward as the angle of attack increases. Boundary layer transition on the model surface can be confirmed by examining the variation in total pressure measured using Preston tubes. The additional roughness drag is estimated from the differences in the axial force coefficients with and without roughness elements at a high absolute angle of attack at which a fully turbulent boundary layer has been confirmed from the measurements using Preston tubes. This additional roughness drag is found to be constant over the entire range of the angle of attack. The drag polar curve can then be shifted by the estimated amount of additional roughness drag and fully turbulent $C_{D_{\text{min}}}$ can be obtained without including the additional roughness drag. The effectiveness of this method is assessed by comparing the values of $C_{D_{\text{min}}}$ corrected using this method with those corrected using the conventional method. Assessment was based on tests conducted at Mach 1.4 in the JSWT and JTWT using the S3TD model and two AGARD-B calibration models having different reference diameters.

2. Apparatus

2.1. Wind tunnels

Wind tunnel tests were conducted in the JSWT and the JTWT at Mach 1.4. The JSWT is a blow-down-type supersonic wind tunnel with solid walls. The JTWT is a closed-circuit continuous transonic wind tunnel, and the test section of the No. 4 cart with porous walls was used. It is not necessary to apply buoyancy correction in either wind tunnel, because the static pressure gradients in the flow around the model are negligible at supersonic speeds. There is no wall interference in either wind tunnel, because the model blockage ratio to the cross-sectional area of the JTWT is very small and the airflow is supersonic in both wind tunnels. The validity of the data obtained from both wind tunnels has recently been confirmed by comparison with data from other wind tunnels in Japan and abroad. Therefore, the difference in the values of $C_{D_{\text{min}}}$ obtained from the tests conducted in the JSWT and JTWT at Mach 1.4 during the S3TD development tests are considered free from the influence of wind tunnel characteristics.

2.2. Models

A 5% scale model of the S3TD is shown in Fig. 1. The model is 690 mm long and has a wing span of 352.8 mm. An internal balance is set in the engine nacelle and the model is supported by a backward sting. Tests were conducted using the model with and without roughness elements. Disk-type roughness elements with roughness heights of $k = 50$, 114 and 142 μm were employed. The diameter and center distances of the roughness elements were 1.5 mm and 3.0 mm respectively, for all cases. The roughness elements were attached to the fuselage at 5% of its length, to the wings at 5% chord, and to the engine air-intake cap at 5% of its length in both JSWT and JTWT. To observe the boundary layer transition, the pressure coefficient of the total pressure in the boundary layer, $C_p$, was obtained from measurements using 12 Preston tubes at three wing stations located at $\eta = 0.30$, 0.50, and 0.75 in the span-wise direction; where $\eta$ is the fraction of the semi-span length. The Preston tubes were attached 10 mm downstream of the roughness elements on the upper and lower surfaces of both wings. Figure 2 shows the plan view of the model with the roughness elements and Preston tubes fitted. The $C_p$ curves show a fairly sharp increase in the transition region.

Two AGARD-B calibration models with reference diameters of 0.045 m and 0.075 m were also tested. These two models are hereafter referred to as the $D = 45$ model and $D = 75$ model, respectively. The planform of the AGARD-B calibration model is shown in Fig. 3. The Reynolds number in the JSWT can be matched to that in the transonic wind tunnel, and the test section of the No. 4 cart with porous walls was used. It is not necessary to apply buoyancy correction in either wind tunnel, because the static pressure gradients in the flow around the model are negligible at supersonic speeds. There is no wall interference in either wind tunnel, because the model blockage ratio to the cross-sectional area of the JTWT is very small and the airflow is supersonic in both wind tunnels. The validity of the data obtained from both wind tunnels has recently been confirmed by comparison with data from other wind tunnels in Japan and abroad. Therefore, the difference in the values of $C_{D_{\text{min}}}$ obtained from the tests conducted in the JSWT and JTWT at Mach 1.4 during the S3TD development tests are considered free from the influence of wind tunnel characteristics.
JTWT considering the model size and total pressure ($P_0$) in each wind tunnel. The Reynolds number based on the model reference diameter was $9.0 \times 10^6$ both at $P_0 = 150$ kPa for the $D = 45$ model in the JSWT and at $P_0 = 107$ kPa for the $D = 75$ model in the JTWT. It was therefore unnecessary to correct for the difference in skin friction due to the difference in Reynolds number. Disk-type roughness elements of $k = 50, 79,$ and $142$ $\mu$m were used in the JSWT tests. Additionally, a two-dimensional roughness element (1.5-mm-wide tape) with $k = 110$ $\mu$m was also used as a roughness element. Disk-type roughness elements of $k = 114, 142,$ and $218$ $\mu$m were used in the JTWT. The roughness elements were attached to the fuselage at 15% of its length, and to the wings at 15% chord length for both JSWT and JTWT tests. The $C_p$ at the boundary layer on the models was obtained from measurements using Preston tubes at six points: four points on the wings (on the upper and lower surfaces of each wing at $\eta = 0.50$) and two points on the nose (on the upper and lower surfaces). The Preston tubes on the wings and the nose were located 10 mm downstream of the roughness elements on both models.

Figure 4 shows the relationship between the aerodynamic coefficients in the body axes and stability axes.

$$C_D = C_N \sin \alpha + C_A \cos \alpha$$

$$C_l = C_N \cos \alpha - C_A \sin \alpha$$

Fig. 4. Relationships between aerodynamics coefficients in body axes and stability axes.

3. Results and Discussion

3.1. Repeatability of $C_D$ measurements

An example of the repeatability of $C_D$ measurements for the S3TD model in the JSWT, with and without roughness elements, is shown in Fig. 5. The repeatability is poorer without roughness elements because the location of boundary layer transition is unstable at angles of attack around $C_{Dmin}$; hence, roughness elements should be applied to fix the location of the transition. In addition, it is confirmed that $C_L$, $C_m$ and $C_N$ are not affected by the presence of roughness elements.

3.2. Total pressure measurements in boundary layer

Curves showing $C_p$ versus $\alpha$ on the upper surface of the right wing are plotted in Fig. 6. These curves were obtained from pressure measurements using the Preston tubes on the upper surface of the S3TD model’s right wing at $\eta = 0.30$ in the JSWT. The values of $C_p$ obtained without roughness elements are lower than those obtained with roughness elements over the angle of attack range of $0^\circ < \alpha < 4^\circ$; hence, it can be inferred that without roughness elements, the boundary layer is still laminar at the tips of the Preston tubes. On
the boundary layer can be considered to be turbulent for the roughness elements of $k = 50$, 114 and 142 $\mu$m are attached, the boundary layer at the tips of the Preston tubes is considered to be turbulent over the angle of attack range of $-4^\circ < \alpha < 10^\circ$, since there are no dips in the $C_p$ curves, as observed in the cases without the roughness elements. Furthermore, even without the roughness elements, the boundary layer can be considered to be turbulent at $\alpha < 0^\circ$ and $\alpha > 4^\circ$ since the $C_p$ curves with and without roughness elements show almost the same behaviors.

Figure 7 shows the $C_p$ values determined from pressure measurements using the Preston tubes on the lower surface of the S3TD model’’s right wing at $\eta = 0.30$ in the JSWT. The results are similar to those obtained for the upper surface, although there is a difference in the range of the angle of attack for which the $C_p$ curve without roughness elements shows a dip. The result at $\eta = 0.50$ shows the same tendency as that at $\eta = 0.30$ in the JSWT. Similarly, the $C_p$ curves for the upper and lower surfaces of the S3TD model’’s right wing at $\eta = 0.30$ in the JTWT are shown in Fig. 8 and Fig. 9, respectively. The dips in the $C_p$ curves without roughness elements and with roughness element ($k = 50 \mu$m), seen at low angles of attack in the figures, can be considered to indicate a laminar boundary layer. Furthermore, the boundary layer is considered to be turbulent for the roughness elements of $k = 114$ and 142 $\mu$m over the angle of attack range of $-4^\circ < \alpha < 10^\circ$. The boundary layer in the range of $7^\circ < \alpha < 10^\circ$ is considered to be turbulent on both the upper and lower wing surfaces even without roughness elements since the $C_p$ values are almost the same as in the cases with roughness elements. The $C_p$ values shown in Figs. 6 and 7 (measured in JSWT) and those shown in Figs. 8 and 9 (measured in JTWT), are quite different since these values depend on the Reynolds number and locations of the Preston tubes in the tests conducted in the JSWT and JTWT. The results of flow visualization on the delta wing with roughness elements, obtained by applying a subliming chemical used in the study by Aga and Robert,\(^\text{1}\) reveal that turbulent wedges appear at the roughness elements. Similarly, longitudinal vortices were expected to occur immediately downstream of the roughness elements in our tests. Moreover, the leading-edge vortices do not directly influence the present results at $\eta = 0.3$ shown in Figs. 6–9. This is because the $C_p$ values are similar, although the relative positions of the tip of the Preston tubes and roughness elements are not adjusted precisely in the span-wise direction. The $C_p$ curves at $\eta = 0.50$ for the upper and lower wing surfaces show the same tendency as that for $\eta = 0.30$ in the JTWT. The behavior of $C_p$ at $\eta = 0.75$, however, could not be evaluated since a vortex shed from the kink at the wing’s leading-edge disturbed the total pressure measurements.

If the results at $\eta = 0.30$ and 0.50 are assumed to represent the behavior of the boundary layer over the entire wing and body of the model, the boundary layer over the roughness elements of $k = 50$, 114 and 142 $\mu$m in the JSWT and the boundary layer of $k = 114$ and 142 $\mu$m roughness elements in the JTWT can be considered to be fully turbulent over the angle of attack range of $-4^\circ < \alpha < 10^\circ$. Furthermore, it can be considered that the difference in the drag coefficients with and without roughness elements is attributable entirely to additional roughness drag since the Preston tube measurements indicate that the boundary layer is turbulent at high absolute angles, regardless of whether or not roughness elements are used. These assumptions form the basis of a method to esti-

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Fig. 7. Changes in $C_p$ on the lower surface of the right wing of the S3TD model at $\eta = 0.30$ in the JSWT.

Fig. 8. Changes in $C_p$ on the upper surface of the right wing of the S3TD model at $\eta = 0.30$ in the JTWT.

Fig. 9. Changes in $C_p$ on the lower surface of the right wing of the S3TD model at $\eta = 0.30$ in the JTWT.
mate the values of $C_{D_{\text{min}}}$ for the fully turbulent boundary layer, excluding the additional drag caused by the roughness elements. In this study, using results of $C_L$ in the tested range of the angle of attack, it was confirmed that there were few areas of boundary layer separation on the S3TD model and the AGARD-B models. If there is a boundary layer separation, the roughness drag can not be calculated. It is necessary to confirm whether or not there is a separation from the results of pressure distribution or the results of force measurements.

### 3.3. Polar curve and polar shift method

If it is assumed that the additional drag caused by roughness elements at a high absolute angle of attack is constant over the entire range of the angle of attack in the wind tunnel tests, the polar curve with roughness elements can be shifted in the negative direction of $C_D$ to eliminate the additional roughness drag. An example of a shifted polar curve for the S3TD model having the roughness element of $k = 142 \mu m$ in the JSWT is shown in Fig. 10. The horizontal axis shows drag coefficient $C_D$ and the vertical axis shows lift coefficient $C_L$. When $C_L$ is low, the angle of attack is also low. When the polar curve for the model having the roughness element of $k = 142 \mu m$ is shifted along the horizontal axis to some extent, it matches with the polar curve without the roughness elements at high absolute angle of attack because the boundary layer is fully turbulent at high absolute angle of attack regardless of whether or not roughness elements are attached. On the other hand, there are differences in $C_D$ at low $C_L$ or a low angle of attack between the shifted curve and the curve without roughness elements. This is because regions of laminar flow exist in the model without roughness elements at a low angle of attack. This result is consistent with the Preston tube measurements.

As shown in the equations in Fig. 4, the difference in $C_D$ with and without roughness elements is almost the same as the difference in $C_A$ with and without roughness elements. This is because $C_S$ is not affected by the presence of roughness elements, as explained in Section 3.1, and the value of $\cos \alpha$ is almost 1 in the tests. Therefore, the additional drag caused by the roughness elements can be estimated by subtracting the values of $C_A$ measured without roughness elements from the values of $C_A$ measured with roughness elements at a high absolute angle of attack. Further details of this procedure are given in the application example described in Section 3.5. This is called the “polar shift method.”

### 3.4. Correction for difference in skin friction due to difference in Reynolds number

If the data acquired at different Reynolds numbers are to be compared, it is necessary to correct $C_{D_{\text{min}}}$ for the difference in skin friction due to the difference in the Reynolds numbers after making the correction for the additional roughness drag. For the S3TD model, the skin friction coefficients are corrected using the following empirical equation, which is applicable to a fully turbulent boundary layer over a flat plate (Prandtl Hoerner’s equation\(^{(10)}\)):

$$C_f = \frac{1}{S_{\text{ref}}} \sum_i \left[ \frac{0.455}{(\log_{10} Re_i)^{1.58}} \left( 1 + 0.144 M^2 \right)^{0.58} S_{\text{wet},i} \right]$$  \hspace{1cm} (1)

where $S_{\text{ref}}$ is a reference area (the wing area) and $Re_i$ is the Reynolds number at each part of the model. $Re_i$ is calculated using the reference length, free stream velocity, viscosity coefficient, and density. The viscosity coefficient is calculated from static temperature using Sutherland’s equation. $S_{\text{wet},i}$ is the wetted area of each part of the model. Prandtl Hoerner’s equation is extensively used in several development tests.

For the S3TD model at Mach 1.4, the value of $C_f$ in the JSWT test at $P_0 = 150 \text{kPa}$ is 0.0017 lower than that in the JTWT test at $P_0 = 80 \text{kPa}$. Therefore, this difference is added to the values obtained in the JSWT for comparison with the JTWT data.

### 3.5. Application to S3TD model tests

The polar shift method proposed was applied to the results of the wind tunnel tests using the S3TD model. The difference in the axial force coefficient ($\Delta C_A$) with and without roughness elements in the JSWT test is shown in Fig. 11. The maximum values of $\Delta C_A$ are seen around an angle of attack of $2.5^\circ$ for the model with roughness elements. The values of $\Delta C_A$ around this angle of attack include both dif-

![Fig. 10. Shifted polar curve of the S3TD model having a roughness element of $k = 142 \mu m$ in the JSWT.](image)

![Fig. 11. Additional roughness drag of the S3TD model in the JSWT estimated by $\Delta C_A$.](image)
ference in skin friction due to the differences in the laminar flow regions and additional roughness drag. As the angle of attack increases above or decreases below 2.5°, the laminar boundary layer on the model without roughness elements becomes turbulent, and the proportion of laminar flow over the surface decreases. Finally, the values of $\Delta C_A$ become constant after the absolute angle of attack reaches a sufficiently high value. In this range of the angle of attack, these constant values can be considered to represent only the additional roughness drag, without including the difference in skin friction due to the differences in the laminar flow regions.

The additional roughness drag for each roughness height was estimated in the high absolute angle of attack range where the standard deviation of $\Delta C_A$ was within 0.0001. This criterion to determine the range of angle of attack was applied to the JSWT and JTWT tests. Figure 12 shows the result of corrections made for the additional roughness drag. The values of the additional roughness drag in the JSWT with roughness heights of $k = 50, 114$, and $142 \mu m$ were 0.00058, 0.00108, and 0.00148, respectively. These values are constant for all the angles of attack. The averaged value of $C_{D_{\text{min}}}$ after these corrections was 0.0330 in the JSWT.

A similar procedure was applied to the JTWT test data. Figure 13 shows the difference in $\Delta C_A$ with and without roughness elements in the JTWT. The values of $\Delta C_A$ are constant at sufficiently high angle of attack where the boundary layer is fully turbulent. Figure 14 shows the result of corrections for the additional roughness drag. The values of the additional roughness drag in the JTWT with roughness heights of $k = 50, 114$, and $142 \mu m$ were 0.00155, 0.00275, and 0.00332, respectively. The averaged value of $C_{D_{\text{min}}}$ after these corrections was 0.0319 in the JTWT.

Table 1 presents the corrected values of $C_{D_{\text{min}}}$ for the S3TD model. In the JSWT, the uncorrected $C_{D_{\text{min}}}$ at $P_0 = 150$ kPa and with a roughness height of $k = 50 \mu m$ is 0.0306, and the $C_{D_{\text{min}}}$ corrected for the additional roughness drag is 0.0303. In the JTWT, the uncorrected $C_{D_{\text{min}}}$ at $P_0 = 80$ kPa and with a roughness height of $k = 142 \mu m$ is 0.0352, and the corrected $C_{D_{\text{min}}}$ is 0.0319. As mentioned in Section 3.4, the value of $C_{D_{\text{min}}}$ in the JSWT is 0.0017 smaller than in the JTWT due to the difference in the Reynolds number. The value of $C_{D_{\text{min}}}$ in the JSWT is 0.0320 after correcting for the skin friction. The discrepancy in the $C_{D_{\text{min}}}$ values measured in the two wind tunnels reduced from 0.0046 to 0.0001 using the polar shift method. This value is

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Mach number} & JSWT & JTWT & $\Delta C_{D_{\text{min}}}$ \\
\hline
1.4 & 1.4 & & \\
\hline
$k$ (kPa) & 150 & 80 & \\
\hline
$\ell$ ($\mu m$) & 50 & 142 & \\
\hline
Uncorrected & 0.0306 & 0.0352 & 0.0046 \\
\hline
Corrected for additional roughness drag by polar shift method & 0.0303 & 0.0319 & \\
Corrected for additional roughness drag by extrapolation method & 0.0299 & 0.0323 & \\
Corrected for skin friction due to the difference in Reynolds number & 0.0017 & & \\
\hline
Corrected for additional roughness drag by polar shift method and for skin friction due to the difference in Reynolds number & 0.0320 & 0.0319 & 0.0001 \\
Corrected for additional roughness drag by extrapolation method and for skin friction due to the difference in Reynolds number & 0.0316 & 0.0323 & 0.0007 \\
\hline
\end{tabular}
\caption{Summary of the corrected values of $C_{D_{\text{min}}}$ for the S3TD model.}
\end{table}
smaller than the difference in $\Delta C_{D\text{min}}$ corrected by the extrapolation method (0.0007). The difference corrected by the polar shift method is also within the uncertainty of the $C_{D\text{11}} (\pm 0.0004)$ in the JSWT or the $2\sigma$ of the $C_{D\text{0}} (\pm 0.0003)$ in the JTWT. This result shows that the polar shift method is acceptable for correcting for additional roughness drag in S3TD model test data.

3.6. Application to AGARD-B model tests

As mentioned in Section 3.4, the difference in the $C_T$ values obtained during the JSWT and JTWT tests using the S3TD model is 0.0017. This is due to the difference in the Reynolds number. To eliminate the effect of Reynolds number, an experiment was conducted using the AGARD-B models with the same Reynolds number ($Re = 9.0 \times 10^6$). A turbulent boundary layer was confirmed based on the measurements using Preston tubes. After confirming the presence of turbulent boundary layer at the tip of the Preston tubes, a fully turbulent boundary layer was assumed on the surface of the AGARD-B models at high absolute angle of attack. The difference in the values of $\Delta C_A$ with and without the roughness elements for the $D = 45$ model in the JSWT is shown in Fig. 15. Figure 16 shows the result of corrections for the additional roughness drag. The values of additional roughness drag for the disk-type roughness elements of $k = 50$, 79 and 142 $\mu$m in the JSWT were 0.00147, 0.00182, and 0.00247, respectively. The additional roughness drag for the line-type roughness element of $k = 110 \mu$m was 0.00189. The corrected averaged value of $C_{D\text{min}}$ with the disk-type roughness elements was 0.0289 for the JSWT. The corrected value of $C_{D\text{min}}$ with the line-type roughness element was similar to that with the disk-type roughness elements. This result shows that the method proposed can correct $C_{D\text{min}}$ even when two-dimensional roughness elements are used, if a turbulent boundary layer is confirmed.

The difference in $\Delta C_A$ with and without roughness elements for the $D = 75$ model in the JTWT is shown in Fig. 17. The values of additional roughness drag for the disk-type roughness elements of $k = 114$, 142 and 218 $\mu$m for the $D = 75$ model in the JTWT were 0.00121, 0.00159, and 0.00157, respectively. Figure 18 shows the result of corrections for the additional roughness drag. The averaged value for $C_{D\text{min}}$ after these corrections was 0.0294 for the JTWT. Table 2 presents the corrected values for $C_{D\text{min}}$. The difference in $C_{D\text{min}}$ values obtained for the JSWT and JTWT tests when corrected by the polar shift method was reduced from 0.0013 to 0.0005. This value is smaller than the difference in $\Delta C_{D\text{min}}$ corrected by the extrapolation method (0.0013). The $C_{D\text{min}}$ corrected by
polar shift method is also within the uncertainty 

of \(C_D\) in the JSWT. This result validates the polar shift method for correcting the test data of the AGARD-B model.

This method can be applied to conventional commercial airplane configurations having a large aspect ratio if the boundary layer is not separated and is turbulent, both with and without roughness elements, at a high angle of attack. Furthermore, the additional roughness drag can be estimated from wind tunnel data obtained for a single roughness height. This is because the variation in the corrected \(C_{D_{min}}\) obtained using this method for different roughness heights is very small. On the other hand, the extrapolation method requires data for several roughness heights.

### 4. Conclusions

A method to correct wind tunnel test data for additional drag due to roughness elements in a fully turbulent boundary layer was proposed.

The result of total pressure measurements using Preston tubes showed that the boundary layer on the wind tunnel model is turbulent at a high absolute angle of attack, regardless of whether or not roughness elements are attached. It is therefore assumed that the difference in the drag coefficients measured with and without the roughness elements at a high absolute angle of attack is due solely to the additional roughness drag. The differences in the axial force coefficients with and without roughness elements were almost constant at a sufficiently high absolute angle of attack. These constant values can be considered to represent only the additional roughness drag, without including the difference in skin friction due to the differences in the laminar flow regions over the model’s surface. When the drag polar curve obtained from the model with roughness elements was shifted along the \(C_D\) axis to eliminate the influence of the additional roughness drag, the shifted and unshifted drag polar curves without the roughness elements matched at a high absolute angle of attack, whereas there was a difference in the \(C_D\) values at low values of \(C_L\), or a low angle of attack, due to the differences in the laminar boundary layer regions. This result was consistent with the Preston tube measurements.

Based on these findings, the values of \(C_{D_{min}}\) for a fully turbulent boundary layer without additional roughness drag were estimated using the polar shift method proposed and assessed applying two types of models in the two wind tunnels. The differences in the values of \(C_{D_{min}}\) corrected using the polar shift method were smaller than those corrected by the conventional extrapolation method, and were well within the uncertainty in the drag coefficient. Therefore the polar shift method successfully corrects the additional roughness drag. In addition, the method proposed is suitable for conducting development wind tunnel test campaigns in a limited time because the additional roughness drag can be corrected using the data obtained using a single roughness height.

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K. Sawada
Associate Editor

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