

Experimental Analysis on the Transitional Mechanism of the Wake Structure of the Ahmed Body

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ABSTRACT

The critical change in drag occurs in the Ahmed Body at 30° of the slanted base due to the transition in the wake structure. The distinctive feature of this bi-stage phenomenon, which consists of three-dimensional and quasi-axisymmetric separation states, is that the state drastically changes. Because this feature indicates that each state is stable around a critical angle, the transition is believed to be triggered by some instantaneous disturbances. Therefore, in our previous papers, we have paid attention on the unsteady behavior of the wake to determine the trigger that induces the transition. However, the relationship between the spatial transient behavior of the wake structures and the specific frequencies has not been clarified. Then, we tried to control the degree of interaction of the trailing vortices on the downwash by changing the aspect ratio of the slanted base.

In the first half, we studied the effects for typical combinations of the slant angle and aspect ratio and conducted an investigation to clarify the relationship between the geometric condition and the transition in the wake structure. In the second half, we conducted an investigation to clarify whether this instantaneous flow structure was caused by the periodic fluctuation of the downwash and trailing vortices or generated by aperiodic fluctuation, which was not involved in the periodic fluctuation. Finally, based on the above-mentioned investigations of the wake-structure behavior, we propose a hypothesis of the transitional mechanism.

CITATION: Kohri, I., Kobayashi, Y., Kasai, A., Nasu, T. et al., "Experimental Analysis on the Transitional Mechanism of the Wake Structure of the Ahmed Body," *SAE Int. J. Passeng. Cars - Mech. Syst.* 9(2):2016, doi:10.4271/2016-01-1591.

INTRODUCTION

The critical change in drag that occurs in the Ahmed Body (Fig. 1) at 30° of the slanted base is due to the transition in the wake structure [1]. At slightly below a 30° slant angle, the coefficient of aerodynamic drag C_D shows a high value, whereas this value is low at slightly above 30°. Ahmed classified the wake structure into two states, namely, three-dimensional separation (TDS) state in the range below 30° and quasi-axisymmetric separation (QAS) state in the range above 30°. He explained that the critical change in the drag corresponds to the sudden transition in the flow state from TDS to QAS. He also clarified that a pair of trailing vortices, a downwash, and an upwash appear behind the body in the TDS state, and these significant structures disappear in the QAS state. However, why the transition occurs at a specific angle of the slanted base has not been clarified.

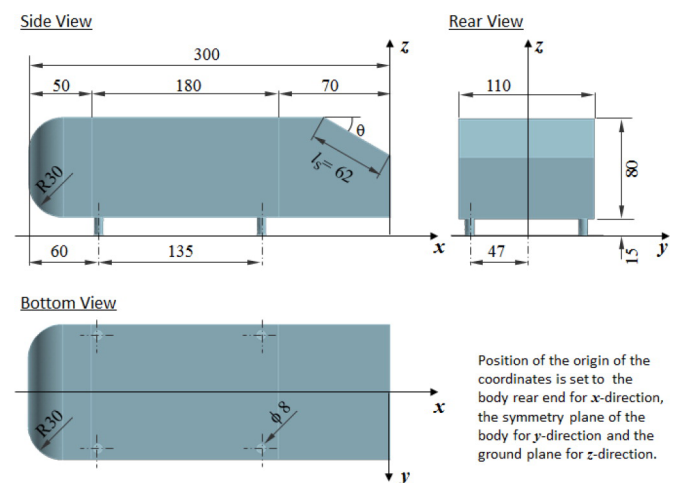


Figure 1. Dimension of the Ahmed Body and coordinate system in this work. This is a one-third scale model of the original model and a test piece for this study.

At any rate, the transition concept is based on the fact that the downwash separates at the top of the slanted base and reattaches somewhere on the slanted base below the critical angle, whereas it does not reattach any more beyond the critical angle. With regard to the flow separation/reattachment of the downwash, it occurs at a much smaller slant angle for a two-dimensional flow. Nevertheless, it occurs at 30° for a three-dimensional flow in the Ahmed Body. This result indicates that the critical angle is strongly dependent on the three-dimensional separated flow. Considering the wake structure explained by Ahmed, the factor that sustains the flow reattachment on the slanted base up to 30° is believed to be a pair of trailing vortices. The physical mechanism for this phenomenon is considered to be common to that of a delta wing [2]. Therefore, we expect that the critical phenomenon occurs only when some specific conditions are satisfied. The conditions are considered to be the relationship between the magnitude of the lateral vortex, which is generated when the downwash separates at top of the slanted base, and the degree of interaction between the trailing vortices and the downwash. Thus, the reattachment of the downwash should be dominated by the degree of interaction of the trailing vortices with the downwash. From this perspective, the slant angle can be assumed as the parameter that governs the degree of interaction of the trailing vortices. Similarly, the aspect ratio of the slanted base can also be considered as another geometric parameter. Johnson [3] investigated the effects of the aspect ratio using computational fluid dynamics (CFD), but he did not validate them by experiment. Venning [4] studied the effects of the aspect ratio in detail at 25° slant angle and clarified the degree of interaction between the downwash and trailing vortices. Then, in the first half of the present work, we validate these effects for typical combinations of the slant angle and aspect ratio and analyze the interaction between the trailing vortices and downwash.

The distinctive feature of this bi-stage phenomenon, which consists of the TDS and QAS states, is that the state drastically changes at the critical slant angle. Because this feature indicates that each state is stable around the critical slant angle, we estimate that the transition is triggered by some instantaneous disturbances. Therefore, in [5] and [6], we paid attention to the unsteady behavior of the wake to determine the trigger that induces the transition.

Sims-Williams [7][8] measured the unsteady behavior of the vortices to identify some distinctive characteristics of their motion. Few years later, he showed the transient behavior of the detailed wake structure very close to the slanted base [2]. During the same period, Vio [9] also measured a detailed transient vortex structure near the surface at 25° and estimated it at the critical angle. In a previous paper, we showed the existence of individual frequencies corresponding to several typical wake structures and clarified the dependence of the slant angle on their specific frequencies by hot-wire measurement. However, the correlation between the spatial transient behavior of the wake structures and the specific frequencies has not been well known yet. Then, in the second half of the current study, we conducted an investigation to clarify whether this instantaneous flow structure is

due to the periodic fluctuation in the downwash and trailing vortices or is generated by the aperiodic and irregular fluctuation that is not involved in the periodic fluctuation.

EXPERIMENTAL FEATURES AND CONDITIONS

A series of experiments was conducted in a small wind tunnel at Tokyo City University (TCU), as shown in Fig. 2. The size of the nozzle was $366 \text{ mm} \times 366 \text{ mm}$, and the test section was $1800 \text{ mm (L)} \times 900 \text{ mm (W)} \times 900 \text{ mm (H)}$. The distance from the nozzle to the center of the model was 450 mm . The maximum wind speed was 25 m/s , and the turbulence was approximately 0.5% at the inlet nozzle. Aerodynamic force balance was installed under the ground wall of the wind tunnel. The ground plate was 30 mm from the ground wall.

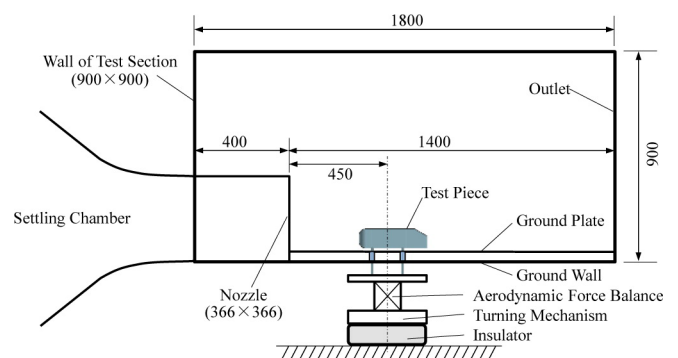


Figure 2. TCU small-scale wind tunnel. The maximum wind speed was 25 m/s , and the turbulence was approximately 0.5% at the inlet nozzle.

The Re number was approximately 7.31×10^4 , which corresponds to a wind speed of 12.0 m/s , where the reference length is the square root of the frontal area ($\sqrt{A}$), u_∞ is the freestream velocity, and ν is the kinematic viscosity of air.

$$Re = \frac{u_\infty \cdot \sqrt{A}}{\nu} \quad (1)$$

The above condition was the regular condition throughout this series of experiments. In the present work, the Re number effects were neglected in investigating this problem, as discussed in a previous paper [6].

Measurement of the aerodynamic forces was conducted using a three-component balance. Particle image velocimetry (PIV) measurements were performed using a Flow Master PIV system (LaVision). Irradiation was conducted using YFL, 33 mJ/pulse with 1-kHz laser (Omicron-Laserage Laserprodukte GmbH), and photographs were taken using HSS-8 with 1024×1024 pixel, 1000-fps camera (LaVision GmbH). Fig. 3 shows the measurement systems used in this study.

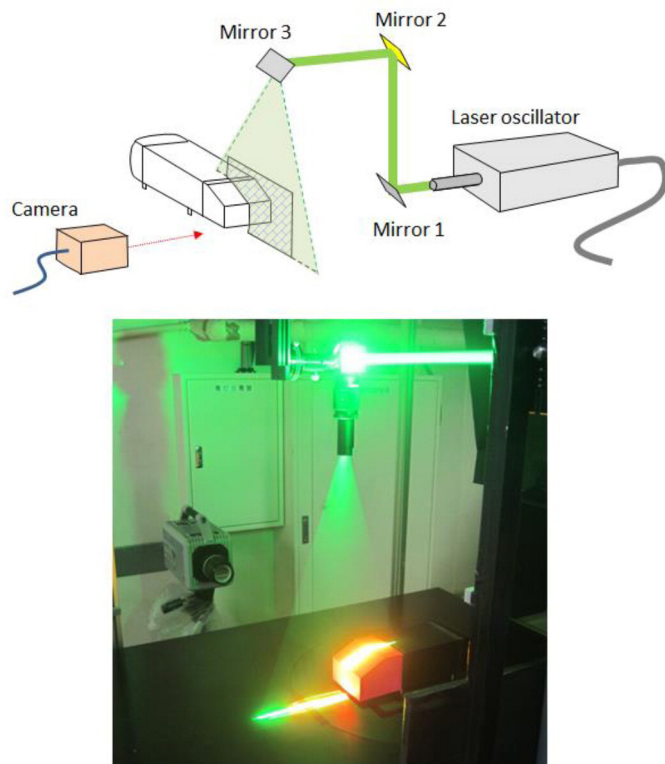


Figure 3. PIV Measurement systems. Measurement of the flow field at the central plane. (Top) Schematic of the system and (bottom) photograph

INTERACTION BETWEEN THE TRAILING VORTICES AND DOWNWASH

As mentioned in the Introduction, the downwash reattachment to the slanted base is dominated by the degree of interaction of the trailing vortices in the downwash. Accordingly, the slant angle can be assumed as the parameter that determines the degree of interaction of the trailing vortices. Similarly, the aspect ratio of the slanted base can also be considered as another geometric parameter. Then, we focus on the aspect ratio of the slanted base, instead of slant angle θ . Here, aspect ratio λ is defined as the ratio of width W of the slanted base to its original length L_s .

$$\lambda = \frac{W}{L_s} \quad (2)$$

In this section, the relationship between these geometric conditions and the transition of the wake structure are discussed.

Preceding Review by CFD Regarding the Aspect Ratio Effects

Johnson [3] systematically discussed the effects of the aspect ratio on the flow state using CFD simulation. He proposed the classification of the wake structure of the Ahmed Body into three states. They are as follows: attached low-drag (ALD) state at slant angle from 0° to 20° where downwash flow separation rarely occurs on the slanted base, high-drag (HD) state from 20° to 30° where the downwash separates from the top of the slanted base and reattaches at the middle, and separated low-drag (SLD) state where reattachment does not occur above 30° . In fact, the ALD state corresponds to a part of the TDS state where the slant angle is below 20° , and the HD state corresponds to a part of the TDS state for slant angle between 20° and 30° . The SLD state is an alternate name of the QAS state.

The systematic calculations by Johnson revealed that the state directly changed from ALD to SLD at a slant angle of 20° when λ was above 1.80, whereas it gradually changed from ALD to HD from 20° to 30° and steeply changed to SLD at 30° when λ was below 1.75, which is the original value of the Ahmed Body. Then, a specific value of λ between 1.75 and 1.80 divided the state above 20° of the slant angle. This transition of state clearly reflects the characteristics of C_L , whose value steeply decreases with the increase in the slant angle around 20° . In contrast, the wake structure changed from ALD to HD above 20° of the slant angle and rapidly changed to SLD at 20° when the aspect ratio was below 1.75, which is the original value of the Ahmed Body. Because the state gradually changed from ALD to HD, C_D and C_L also gradually changed. These characteristics are believed to be caused by the fact that the separated region near the top of the slanted base gradually expands toward the bottom of the slanted base with the increase in the slant angle. According to Johnson's calculation, the transition from HD to SLD is gradual with the increase in the slant angle above 30° for λ below 1.75. When λ was 1.30, C_D and C_L displayed middle values between HD and SLD. Therefore, the critical phenomenon at a slant angle of 30° is believed to be related to some specific values of λ .

Systematic Experimental Study on the Aspect Ratio Effects

We attempted to validate the Johnson's predictions. Three conditions, namely, $\lambda = 1.29$, $\lambda = 1.77$ and $\lambda = 2.26$, were adopted for the validation. The variation in the slant angle is listed in Table 1 and shown in Fig. 6. Because the Re number in our experiments was different from that in the Johnson's calculation, the friction drag indicated a different value from the Johnson's result. However, as presented in our previous paper [6], the friction effects could be ignored when the change characteristics are studied because the change characteristics of an aerodynamic force due to a slanted-base surface are mainly determined by the change in the pressure distribution on the slanted base. Accordingly, the characteristics of the aerodynamic force at any angle were evaluated using the difference from the aerodynamic force at 0° .

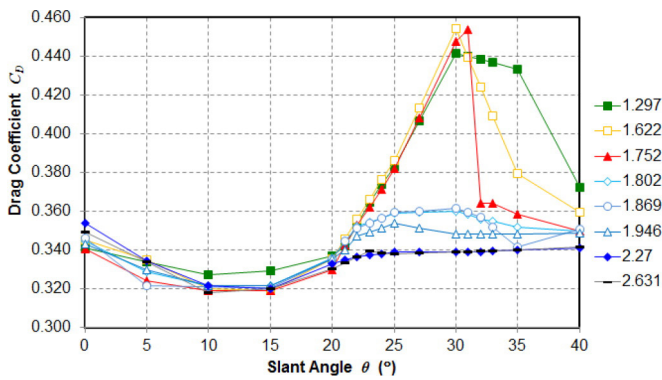


Figure 4. Change in C_D for various aspect ratios. The data are from Johnson's calculation (2004) [3]

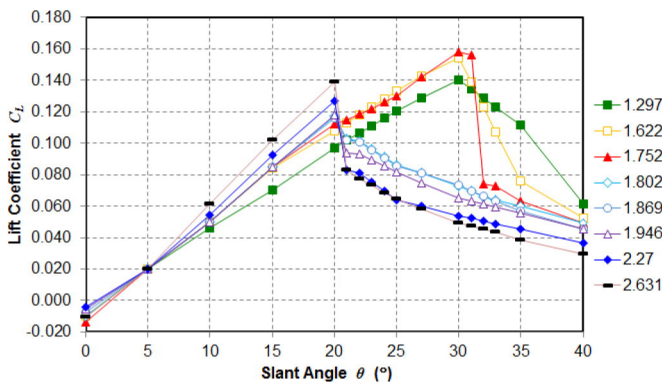


Figure 5. Change in C_L for various aspect ratios. The data are from Johnson's calculation (2004) [3]

Table 1. Variation in the slant angle. Three conditions of $\lambda = 1.29$, $\lambda = 1.77$, and $\lambda = 2.25$ were adopted for the validation using Johnson's calculation.

	Aspect Ratio λ		
	1.29	1.77	2.25
Slant angle θ	0.0	0.0	0.0
	12.5	12.5	12.5
	17.5	17.5	17.5
	22.5	22.5	22.5
	27.5	27.5	27.5
	32.5	30.0	32.5

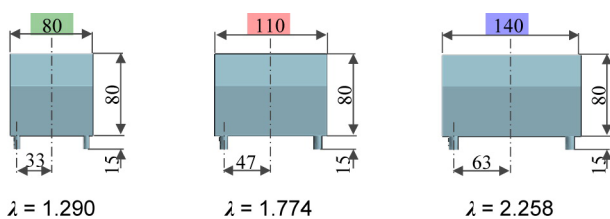


Figure 6. Variation in the aspect ratio. Aspect ratio λ is defined as the ratio of width W of the slanted base to its original length L_s . In this study, L_s is fixed at 63 mm for all variations

Fig. 7 shows that at $\lambda = 1.29$, C_D indicated an HD state at 27.5° slant angle and an SLD (QAS) state at 32.5° . Unfortunately, we could not obtain the data at 30° , but it was clear that transition occurred between 27.5° and 32.5° . Therefore, the tendency of the transition was evidently different from the Johnson's result. Similarly, at $\lambda = 2.25$, the tendency was different. According to our experiments, C_D indicated an HD state at 27.5° (although the absolute value was not very large) and an SLD state at 32.5° . This trend was completely different from the Johnson's result, i.e., C_D represented an SLD state at 27.5° , and an HD state never occurred between 20° and 30° . On the other hand, at $\lambda = 1.77$, which corresponds to the original dimension of the Ahmed Body, the transition phenomenon across a slant angle of 30° was clearly evident in both studies.

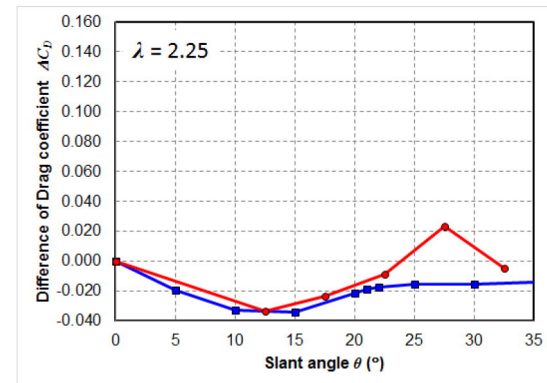
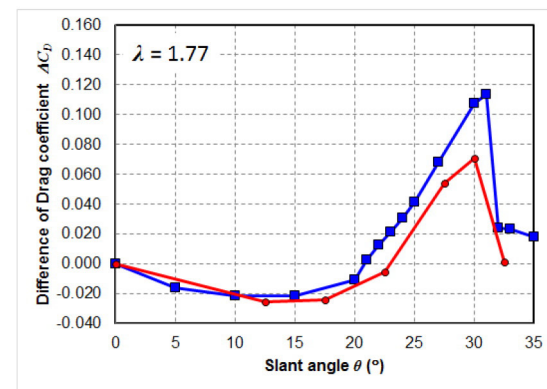
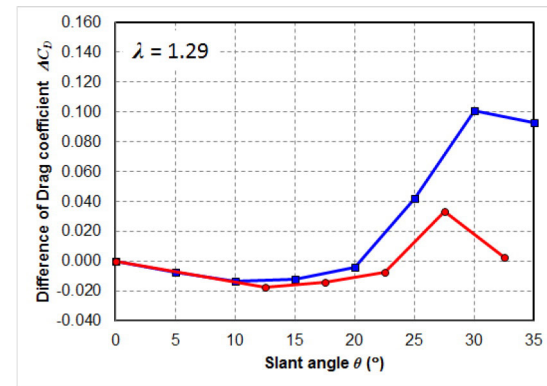


Figure 7. Comparison of the C_D changes for various aspect ratios. Filled squares (■:blue) denote the Johnson's results, and filled circles (●:red) denote the TCU results