Effect of Boattail Angle on Pressure Distribution and Drag of Axisymmetric Afterbodies under Low-Speed Conditions

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This study is focused on the effect of boattail angle on the pressure distribution and drag force of axisymmetric afterbodies under low-speed conditions. Experiments were conducted on three conical boattails with angles of 10°, 14° and 20°. The diameter-based Reynolds number is approximately 4.3 × 10^4 under the experimental conditions. Two types of flows, a fully-attached flow (β = 10°) and a flow with a separation bubble (β = 14°, 20°), were observed. The aerodynamic drag measurements were conducted using both a strut-supported model and a support-free (levitated) model. The results show that boattail model with the angle of 20° has a relatively large effect on the pressure distribution. The pressure drag resulting from pressure distribution on the vertical plane indicates that the model with a boattail angle of 14° has the lowest drag. A good trend in agreement between afterbody drag (measured using pressure taps) and total aerodynamic drag (measured using the levitated system) was obtained. The effect of strut support on pressure distribution at different polar angles is also explained in this study.

Key Words: Axisymmetric Afterbody, Afterbody Pressure Drag, Base Drag, MSBS, Aerodynamic Characteristics

1. Introduction

Axisymmetric blunt-base objects are characterized by a large separation region and unsteady turbulent wake. To improve the aerodynamic performance of the model, modification of the base flow is required. Among many devices for base drag reduction such as base bleed, splitter plates, locked vortex afterbodies, boattail combined with grooved cavities, boattails show good potential. The advantage of the boattail is that it shortens the recirculation length and reduces the near-wake intensity. Consequently, the base pressure increases and base drag is diminished. Additionally, flow field on the boattail surface is also an important parameter that affects drag reduction.

In the early 1980s, Kentfield reported that a conical boattail of 14°, where the flow attaches along the surface, produced small drag. Howard and Goodman also revealed low drag at a boattail angle of approximately 10°. However, at boattail angle of 30°, the flow separated near the shoulder and high drag was recorded. Buresti et al. revealed a steady decrease in afterbody drag when the boattail angle is increased from 10° to 20°. They also noted that, at those configurations, the flow was fully attached to the surface. Mariotti et al., who summarized previous studies under low-speed conditions, stated that at a fixed boattail length, aerodynamic drag decreases with increasing boattail angle until the separation flow is maintained at the base edge. If the boattail angle continues to increase, the separation position moves upstream and drag increases again. Inherently, drag obtains a minimum value around an angle where flow shifts from a...
fully attached condition to a separated condition. Recently, Tran et al.\textsuperscript{14)} was the first to report a type of transition flow between the attached and separated conditions. In that case, a separation bubble is generated near the boattail shoulder while massive separation is seen at the base edge. However, drag force analysis was not performed. Additionally, the limited information in previous studies prevents a systematic explanation of the relation among flow fields, pressure distribution and aerodynamic drag of the model.

The other problem in wind tunnel testing is the effect of the support system.\textsuperscript{15–17)} Clearly, the support system significantly changes the flow behavior of the model and reduces measurement accuracy.\textsuperscript{18)} One way to eliminate the interference effect is to conduct experiments in a support-free, levitated system. A magnetic suspension and balance system (MSBS) that levitates models in space by utilizing magnetic force interaction provides a highly accurate technique for controlling model position and measuring total aerodynamic force.\textsuperscript{19,20)}

The objective of this study is to investigate the effect of boattail angles on the pressure distribution and aerodynamic drag of axisymmetric models under low-speed conditions. Based on previous results of the skin friction,\textsuperscript{14)} three conical boattail models with angles of 10°, 14° and 20° were selected and tested. The flow behavior is characterized by the attached condition (10°) and conditions with a separation bubble (14° and 20°). However, the skin-friction level is remarkably different inside and behind the bubble for those configurations (Fig. 1). The effect of boattail angles on pressure distribution and pressure drag is investigated under a strut-supported condition. Additionally, to eliminate the interference effect, drag measurement is conducted using a support-free, levitated system. The effect of the strut support on pressure distribution at different polar angles is also evaluated.

2. Experimental Setup

2.1. Wind tunnel facility

The experiments were carried out in a low-speed, indraft wind tunnel with a square test section of 300 × 300 mm². A uniform flow was obtained using a combination of honeycomb and mesh systems located upstream of the test section. The speed of the wind tunnel ranged from 5 to 60 m/s and the turbulence intensity was less than 0.5%.

The test section could be removed and replaced by a magnetic suspension and balance system (MSBS) with the same dimensions. The details of force measurement process in the MSBS are presented in Appendix.

2.2. Model and testing conditions

The model had a diameter \( D \) of 30 mm (Fig. 2). The total lengths of the support-free, levitated and strut-supported models (\( L_t = 251–253 \) mm) were slightly different due to the effect of connected parts. The front body was half of a 2:1 ellipsoid. The afterbody could be removed and different conical boattails having the same length (0.7\( D \)) could be added. The boattail angles used were 10°, 14° and 20° (Fig. 2(b)). To trip the boundary layer to become turbulent, a strip of sandpaper P40 10 mm in width was attached to the front section of the model, at 0.15\( L_t \) aft of the nose. The size of grit was chosen following a method proposed by Braslow and Knox.\textsuperscript{21)} A previous study\textsuperscript{22)} at similar Reynolds number to the current study indicated that the size of grit was sufficient to fully trip the boundary layer into turbulence.

The coordinate system is shown in the Figs. 2(a)–2(c). The coordinate was fixed on the main body. The polar angle \( \varphi \) was determined by the angle between the radius line and \( y \)-axis. Here, the polar angle \( \varphi = 90^\circ \) is at the top position, while the angle \( \varphi = 270^\circ \) is at the bottom position, where the strut support is located.

The experiment was performed at a velocity of 22 m/s, producing a diameter-based Reynolds number of approximately \( Re = 4.3 \times 10^4 \). The angle of attack was fixed at 0° for all experiments.

In the pressure measurement process, the model was supported in the test section using a strut (Fig. 2(c)). The parameter of the strut is shown in Table 1. Details of the experimental setup for measuring pressure measurement are illustrated in Section 2.3.1.
2.3. Afterbody pressure measurement

2.3.1. Measurement system

To measure pressure distribution on afterbodies, fifteen pressure taps located on the vertical plane at \( \varphi = 90^\circ \) were utilized (Fig. 3). More specifically, eight taps were placed on the boattail, while the base surface had five taps. Additionally, one pressure tap was placed at the nose of the model to measure stagnation pressure. The taps had a diameter of 0.5 mm and were connected to Pressure Scanner 9116 using silicone tubes. The tubes were 500 mm long, had an inner diameter of 1 mm ran inside the model and strut support, and then out of the test section (Fig. 2(c)).

The pressure scanner had a full-scale system accuracy of 0.05%. The measurement was performed at a sampling frequency of approximately 50 Hz and a total of 5,000 data samples were obtained for each port. Additionally, each measurement was repeated several times. Consequently, the mean values and standard deviation of measurements were calculated.

Finally, the afterbody was designed so that it can be rotated along the x-axis by a step angle of 45\(^\circ\). Accordingly, pressure distribution at different polar angles could be obtained.

2.3.2. Data reduction

The pressure coefficient was calculated using local pressure and stagnation pressure located at the nose of model as follows:

\[
C_{pl} = \frac{P_l - P_0}{\frac{1}{2} \rho u_{\infty}^2} + 1
\]

The method for calculating pressure coefficient from local pressure and stagnation pressure was used by Higuchi et al.\(^{23}\) for a cylinder model in the support-free, levitated test. Since the study concentrated on average values and measurements were performed under low-speed conditions, the results obtained should have been highly accurate. The effect of strut support on the measurement of stagnation pressure and its offset were neglected in this study.

Based on the data of pressure measured, pressure drags were calculated. Additionally, only pressure coefficients located at the polar angle \( \varphi = 90^\circ \) were processed to minimize the effect of strut support on measurements. The boattail pressure drag, which shows pressure drag acting on the boattail surface, was calculated using Eq. (2).\(^{24}\) Since pressure is continuous in subsonic flow and this study focuses on static measurement, the pressure value of the tap located near the base edge \( (r/d_b = 0.48) \) was also used for calculating the boattail pressure drag. The base drag, which shows pressure drag acting on the base, was calculated using Eq. (3). The afterbody pressure drag equals the sum of boattail pressure drag and base drag. Additionally, the total afterbody drag as the sum of afterbody pressure drag and afterbody skin friction drag was also calculated in this study.

\[
C_{Dp,b} = \frac{1}{R^2} \int_{R}^{r_b} C_{p,b}(r)dr^2
\]

where, \( C_{p,b}(r) \) is the pressure coefficient on the boattail surface and \( C_{p,b}(r) \) is the pressure coefficient on the base at \( r \) position and \( \varphi = 90^\circ \) (Fig. 2(a)).

2.4. Afterbody skin-friction drag

Since the base surface was perpendicular to the free-stream velocity, the base skin-friction drag is equal to zero. The afterbody skin-friction drag was equal to the boattail skin-friction drag and calculated using the following equation\(^{25}\):

\[
C_{Df,a} = \frac{1}{8} \int_{0}^{l_a} c_f(x) \cdot 2\pi r dx
\]

where, \( c_f(x) \) is the local skin-friction coefficient at \( x \), as shown in Fig. 1.

3. Results and Discussion

3.1. Pressure distribution and afterbody pressure drag

3.1.1. Effect of strut support on pressure field

Figure 4 shows the pressure distribution at different polar angles for three boattail configurations. The left plot is the pressure coefficient on the boattail surface, and the right plot illustrates pressure distribution on the base radius. Generally, pressure around the shoulder is lower at the bottom position where the strut support is located. This effect is relatively large at \( \beta = 20^\circ \). At the boattail angle \( \beta = 10^\circ \) and polar angle \( \varphi = 270^\circ \), pressure around the base edge increased slightly. The base pressure distribution on the vertical plane revealed similar results observed by Wolf et al.\(^{26}\) for a blunt base, where the high-pressure region was observed in the lower half (negative z-values). It is believed that the wake of the strut support slows the flow velocity in the bottom region, which tilts the afterbody vortex system and results in an increase in base pressure. For two other boattail models, the effect of the strut on base pressure was very small.

Clearly, the strut support had an impact on pressure distribution near the shoulder and lower half of the base. As
shown by Compton and Runckel, the pressure measured with the strut support on the top boattail surface (\(\varphi = 90^\circ\)) obtained very close agreement to the results measured when using sting supports. Although that study was performed at Mach numbers \((M \geq 0.4)\) much higher than in the current study, it supports the concept that the pressure measured at \(\varphi = 90^\circ\) can be used as interference-free data. For this reason, only pressure coefficients at \(\varphi = 90^\circ\) will be used for discussing pressure distribution and pressure drag.

### 3.1.2. Effect of boattail angle on pressure distribution

The effect of boattail angles on the pressure distribution on the boattail and base surfaces at \(\varphi = 90^\circ\) is shown in Fig. 5. Here, the separation and reattachment positions are also marked. The separation and reattachment were determined to be when the azimuthal-averaged skin-friction values (see Fig. 1) changed to negative and positive, respectively. Clearly, the existence of the boattail leads to convex curvature of streamlines above the boundary layer over the lateral surface. Additionally, a low-pressure region with a negative peak of pressure occurs around the shoulder. The decrease in pressure near the shoulder leads to acceleration of the flow above the boattail surface. The flow behavior is similar to the flow along the upper surface of an airfoil under subsonic conditions. The low-pressure region near the boattail shoulder has been widely reported in previous studies for both low-speed\(^9\) as well as high-speed flows.\(^{27}\) Separated positions were directly connected with the pressure gradient changing from negative to positive. Additionally, pressure quickly recovered along the boattail length direction. On the second half of the boattail \((x/L_\beta > 0.6)\) and at angles of \(14^\circ\) and \(20^\circ\), positive pressure coefficients were observed, which lead to the reduction of afterbody pressure drag.

Previous studies of subsonic flow show that the negative peak of pressure becomes lower at higher boattail angles.\(^{1,5,27}\) Similar results were obtained in this study at boattail angles increasing from \(10^\circ\) to \(14^\circ\). It can be explained that the convex curvature of streamlines near the shoulder becomes higher at a higher boattail angle. It led to lower pressure with increasing pressure gradient around the shoulder. However, at \(\beta = 20^\circ\), the pressure gradient near the shoulder was not as steep and the low-pressure region was widened. The separation bubble probably alters the virtual boattail angle, thereby reducing the convex curvature of the streamline above the bubble. The high skin-friction magnitude inside the separation bubble shown in Fig. 1 supports this argument. Note that this pressure trend differs totally with previous studies\(^{(1,27)}\) in high speed and was first observed for axisymmetric conical boattail under low-speed conditions.

At the base, the pressure distribution on each boattail model was relatively constant along the radius. Additionally, the pressure increased with boattail angle. Positive pressures occurring at \(\beta = 14^\circ\) and \(\beta = 20^\circ\) were caused by the high-pressure recovery near the base edge. The positive base-pressure values have also been reported in other afterbody studies.\(^{(28,29)}\)

### 3.1.3. Boattail pressure drag and base drag

The measurement of pressure allows analysis of each component of pressure drag acting on the afterbody. For calculating boattail pressure drag and base drag, Eq. (2) and Eq. (3) presented in Section 2.3.2 were utilized. The results are summarized in Table 2. The afterbody skin-friction drag \(C_{Df,a}\) calculated using Eq. (4) is also listed. Here, \(C_{D,a}\) is the total afterbody drag coefficient, including both pressure and skin-friction components. To demonstrate the effect of pressure distribution on afterbody drag more clearly, plots of relative radius \(r/R\) and radius squared \((r/R)^2\) against pressure coefficient \(C_p\) are also presented in the Fig. 6. The horizontal dashed lines show the position of the base edge. The afterbody pressure drag coefficient was determined by the areas...
The low base drag at present was presented. Compared to the case of 10° force calibration and drag measurement processes are also area of the main body. Uncertainties as the sum of errors in
created using the curves plotted \((r/R)^2\) against \(C_p\) and the vertical line of \(C_p = 0\). Clearly, the base drag of the model with \(\beta = 10^\circ\) is almost zero. At \(\beta = 14^\circ\), boattail pressure drag can be overcome well by positive values at the base. However, at \(\beta = 20^\circ\), a severe drop in pressure was observed on boattail surface (Fig. 6(b)).

The boattail pressure drag shows an upward trend when boattail angle increases. In contrast, the base drag decreased with the increase of boattail angles tested in this study. The skin-friction drag coefficient was one or two orders smaller than the pressure coefficients for all three configurations (Table 2). The total afterbody drag at the boattail angle of \(14^\circ\) was lower than the values at the two other boattail angles of \(10^\circ\) and \(20^\circ\).

### 3.2. Total aerodynamic drag

Although the effect of the strut support on the flow at top surface is limited, it strongly affects the flow along the bottom region (Fig. 4). Measuring force using strut support can lead to large uncertainty.\(^{18}\) Accordingly, the process for measuring drag using the support system becomes sufficiently complicated. To obtain precise drag values, measuring force using support-free, levitated system (0.3-m MSBS) has been conducted.

The results of drag measurement are shown in Fig. 7. Here, drag coefficients are calculated based on cross-section area of the main body. Uncertainties as the sum of errors in force calibration and drag measurement processes are also presented. Compared to the case of \(10^\circ\), the boattail model of \(\beta = 14^\circ\) reduces drag by approximately 5%, while at \(\beta = 20^\circ\) drag increases by approximately 7%. Obviously, the low base drag at \(\beta = 14^\circ\) compensates well for the increase in boattail pressure drag (Table 2). However, at \(\beta = 20^\circ\), the bubble has a dominate effect on afterbody pressure drag. Consequently, total aerodynamic drag increases again.

In this study, the forebody drag (drag of nose and main body) was not measured. However, the forebody drag should be the same for three boattail models. Gerald\(^{30}\) showed that the forebody drag is approximately \(C_{D,\text{fore}} = 0.175\) under similar experimental conditions as the current study.

Since the flow is attached to the surface at boattail angles lower than \(10^\circ\), the total aerodynamic drag should decrease as the boattail angle increases from \(0^\circ\) to \(10^\circ\).\(^9\) Additionally, at boattail angles larger than \(20^\circ\), the flow is fully separated near the shoulder and drag increases.\(^{14}\) Therefore, the minimum drag should exist at boattail angles between \(10^\circ\) and \(20^\circ\). In our observation, the minimum drag occurred at a boattail angle around \(14^\circ\), where the boattail pressure drag was well overcome by the low base drag.

The force measurement results show good trend agreement with the afterbody pressure drag calculated from pressure taps at the polar angle of \(\varphi = 90^\circ\). The drag difference between \(\beta = 20^\circ\) and \(\beta = 10^\circ\) measured by MSBS was higher than measured by pressure taps. An insufficient number of pressure taps and the effect of support system should be factors for this outcome.

### 4. Conclusions

The effect of the boattail angle on pressure distribution and the drag of an axisymmetric model was studied experimentally under low-speed conditions. The major findings are listed as follows:

1) The boattail angle has a large effect on pressure distribution on the afterbody. An increase in boattail angle from \(10^\circ\) to \(14^\circ\) led to a lower negative pressure peak, which was often observed in previous studies. At \(\beta = 14^\circ\), the low base drag compensated well for the increase in boattail pressure drag. However, at \(\beta = 20^\circ\), the pressure gradient near the shoulder was less steep and the low-pressure region

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**Table 2. Components of drag acting on afterbody surface.**

| Angle \(\beta (\degree)\) | \(C_{Dp,\beta}\) | \(C_{Dp,b}\) | \(C_{Df,a}\) | \(C_{D,a}\) |
|--------------------------|----------------|----------------|---------------|-------------|
| 10                       | 0.0331          | 0.0025         | 0.0014        | 0.0370      |
| 14                       | 0.0435          | -0.0206        | 0.0009        | 0.0238      |
| 20                       | 0.0661          | -0.0251        | -0.0003       | 0.0407      |

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**Fig. 6. Surface pressure coefficients on the afterbody.**

**Fig. 7. Aerodynamic drag summary.**
widened. A severe drop in pressure occurred on the boattail surface, leading to an increase in total afterbody drag. The separation bubble on the surface probably alters the virtual boattail angle. This pressure trend differed entirely from previous observations and was first reported in this study.

2) The total aerodynamic drag of axisymmetric boattail models was first measured and evaluated under support-free, levitated condition. Compared to the boattail angle of 10°, the 14° boattail model reduced drag 5%, while the 20° model increased drag to 7%. A minimum drag exists at boattail angles around 14° before the flow is changed to a fully separated condition. The results of the afterbody pressure drag show high consistency with the total drag measured using the 0.3-m MSBS.

3) The existence of strut support led to lower pressure near the shoulder. At the boattail angle of 10°, the pressure distribution around the base was affected by the strut support. However, at higher angles, such effect was not observed.

Acknowledgments

This work was supported by KAKENHI grant (No. 16H04582), KAKENHI grant (No. 18H03809) and JST Presto (No. JPMPPR1678).

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Appendix: The 0.3-m MSBS and Total Aerodynamic Drag Measurement Process

A.1. Outline of 0.3-m MSBS

To measure the total aerodynamic drag acting on the model and eliminate the effect of the support system, the 0.3-m
MSBS was utilized. In this system, ten electric magnets are located outside the test section and one permanent magnet is inserted inside the model. The magnetic system produces forces and moments that enable the model to levitate freely in the test section. Consequently, the interference effect is totally eliminated.

The schematic arrangement of the coils and sensor subsystem is shown in Fig. A1. Ten electrical magnets with a limited current of 15 A are divided into five pairs, which allow the model to be controlled in five degrees of freedom. In detail, movement in the $x$-direction is controlled by currents flowing through coils 0 and 9. The lift force and pitching moment are controlled by the currents flowing through upper and lower coils 1, 3, 5, and 7, while the side and yawing motions are controlled by currents flowing through coils 2, 4, 6, and 8.$^{31}$

The positions and attitudes of the model in the support-free, levitated test were detected by an optical sensor subsystem oriented orthogonally to the model (Fig. A1(b)). The system included five CCD line cameras with a sampling frequency of 620 Hz. The resolution of the sensor system was 7.01 μm and 0.0084°/cm in position and attitude, respectively. The cameras detected the edges of the model and the black marker at the center. The data was then processed to receive the positions and attitude of the model.$^{32}$ To illuminate the edge of the model, four red LEDs and four blue LEDs were used. Additionally, a small blue LED was used to enhance the illumination around the center of the model. In the levitating process, the model was kept stable in the flow by a proportional-integral (PI) controller with a double-phase advancement.

**A.2. Process to measure drag**

A process for measuring drag using 0.3-m MSBS is shown in Fig. A2. Firstly, sensor calibration is performed to obtain the relation between the positions of the model and parameters of the cameras. Secondly, the control parameters are input and the model is levitated freely. To separate the motions of each channel, decoupling parameters are input to the control program in the third step. Drag force calibration is performed in the fourth step. In the fifth step, the attitudes of the model are adjusted to ensure that they coincide in the MSBS and wind tunnel system. In the sixth and seventh steps, wind tunnel testing and data processing are performed. Finally, the drag coefficient is extracted.

**A.3. Drag force calibration**

In the drag force calibration process, weights ranging from 0 to 50 g are connected to the support-free, levitated model using a thread and pulleys system (Fig. A3(a)). Through
the testing process, the relation between forces acting on the model and drag current is obtained. For each boattail angle, drag force calibration is performed six times to eliminate the magnet hysteresis and evaluate measurement error. The results indicate that a highly linear dependence exists between the drag force and coil currents for all three configurations (Fig. A3(b)).

Based on the data from force calibration, the aerodynamic drag acting on the model during wind tunnel testing could be calculated. For each configuration, the experiment is repeated several times and the mean values are obtained.

Jinsoo Cho
Associate Editor